A BPF Map
for
Online Packet Classification

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Linux
Plumbers
Conference
Dublin, Ireland September 12-14, 2022

Outline

- Online packet classification: algorithms
- New map: BPF_MAP_TYPE_WILDCARD
- Pictures, Numbers

Packet Classification

- A classifier: rules + packets
- A Rule: one or more of
    - bitmask/prefix, e.g., 127.0.0.0/8
    - Range, e.g., 1-1024
- Fast lookups

Online Packet Classification

- Fast lookups
- And also fast updates

Use cases

- SDNs, Firewalls, ACLs, Routing, etc.
- Cilium: XDP prefilter
- Cilium: L4LB packet recorder
- Cilium: Network Policies

Cilium: XDP prefilter

- Allows to filter packets at the earliest time
- Limited functionality:
  - only lookups by source IP (hash)
  - *or* by source CIDR (LPM)

Cilium: L4LB packet recorder

- “Wildcard” 4-tuples, but
- Updates may require recompilation
- Doesn’t scale well (linear by #masks)
- Doesn’t support port ranges
- Added BPF complexity!
- See LPC2021 talk by Daniel & Martynas

Cilium: network policies

- K8S 1.25: Promoted endPort in Network Policy to Stable
- We can implement ranges using LPM, but:
    - No real ranges (only prefixes)
    - No support for both src & dst ranges
    - LPM is slower than hash

New Map Design

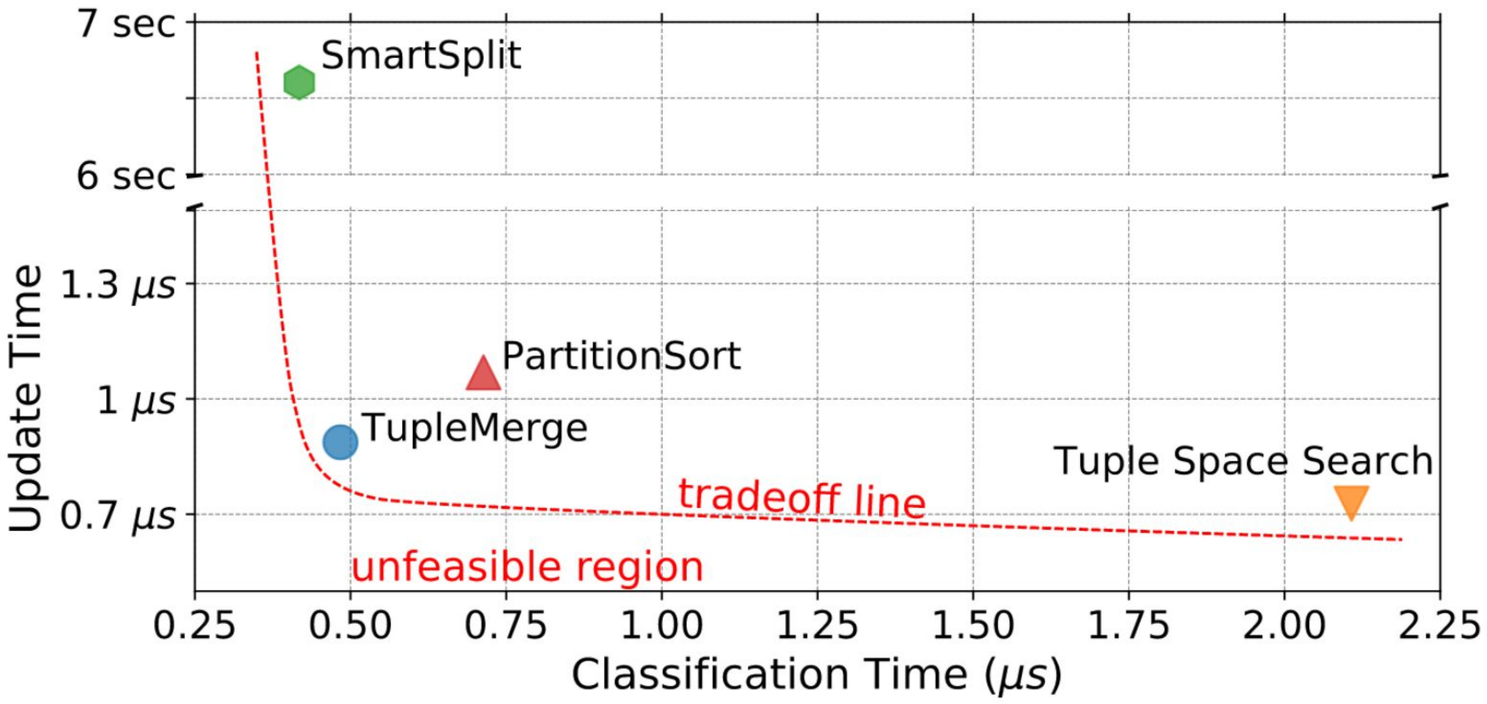
- Supports different wildcard rules and any number of fields
- Complexity: just a map lookup/update
- Fast lookups
- [reasonably] fast updates

Existing Algorithms

- **Brute Force:** actually works when there are just a few rules
- **Hash-based:** TSS (Tuple Space Search) => TM (Tuple Merge)
- **Tree-based:** Partition Sort

TupleMerge: Fast Software Packet Processing for Online Packet Classification
A Sorted Partitioning Approach to High-speed and Fast-update OpenFlow Classification

Existing Algorithms



* The picture is copied from “TupleMerge: Fast Software Packet Processing for Online Packet Classification”

Tuple Space Search

- Say, we have rules of form IP/prefix
- E.g., we have the following set of rules:
  - 172.16.0.0/16
  - 172.17.0.0/16
  - 8.0.0.0/8
  - 10.1.1.0/24
  - 10.2.2.0/24

Tuple Space Search

- We can combine then as follows:
    - T(16): 172.16.0.0, 172.17.0.0
    - T(8): 8.0.0.0
    - T(24): 10.1.1.0, 10.2.2.0

Tuple Space Search

- Packet arrives from 10.2.2.2
    - T(16): 172.16.0.0, 172.17.0.0
    - T(8): 8.0.0.0
    - T(24): 10.1.1.0, 10.2.2.0

Tuple Space Search

- Table-1 lookup: 10.2.2.2 & ffff0000
    - T(16): 172.16.0.0, 172.17.0.0 10.2.0.0
    - T(8): 8.0.0.0
    - T(24): 10.1.1.0, 10.2.2.0

Tuple Space Search

- Table-2 lookup: 10.2.2.2 & ff000000
    - T(16): 172.16.0.0, 172.17.0.0
    - T(8): 8.0.0.0 10.0.0.0
    - T(24): 10.1.1.0, 10.2.2.0

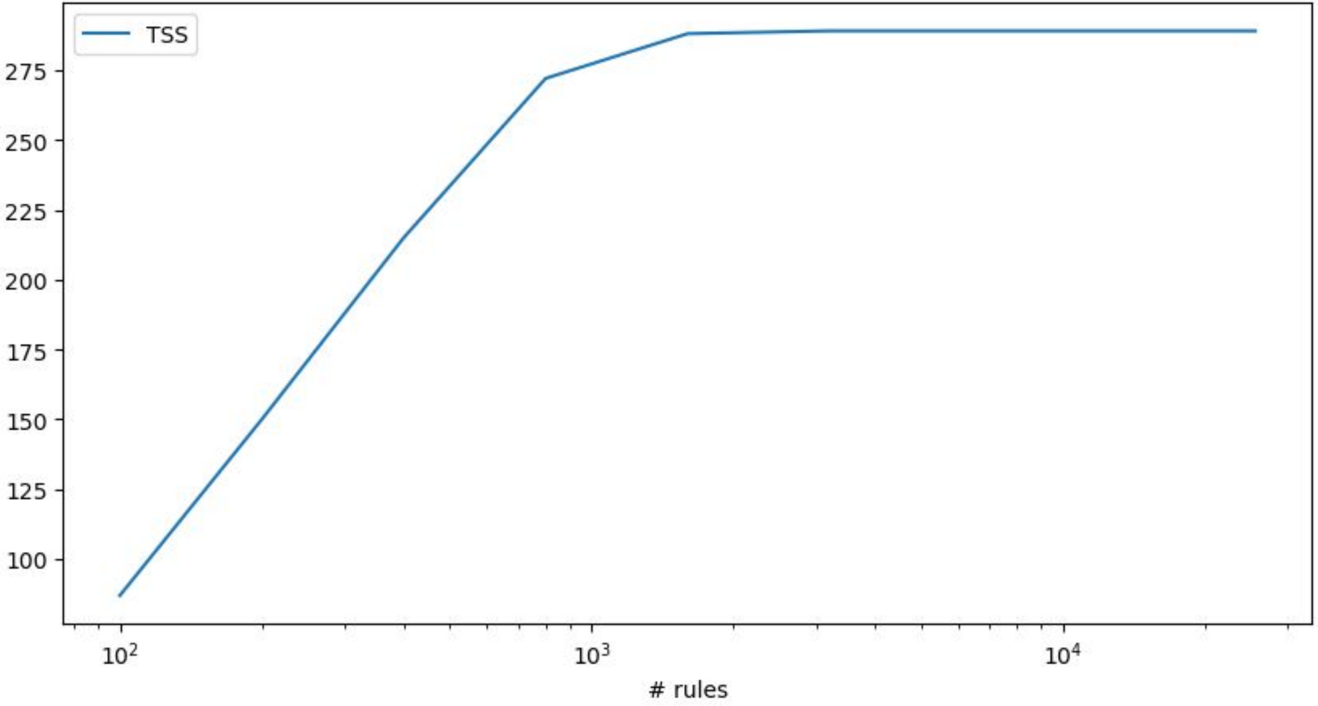
Tuple Space Search

- Table-3 lookup: 10.2.2.2 & ffffff00
    - T(16): 172.16.0.0, 172.17.0.0
    - T(8): 8.0.0.0
    - T(24): 10.1.1.0, 10.2.2.0

Problem with Tuple Space Search

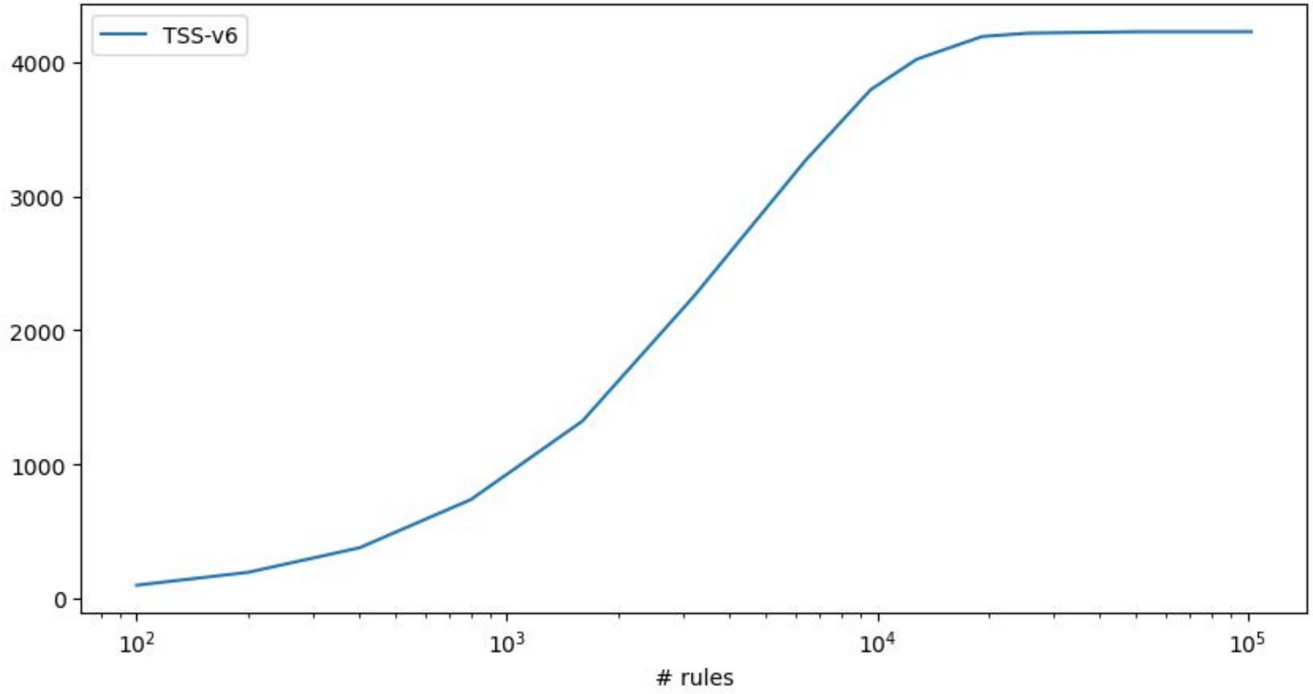
- Each successful lookup requires to search N/2 tables => N/2 hash table lookups
- Each unsuccessful lookup requires to search all N tables

Problems with Tuple Space Search, IPv4



# of tables for TSS for two-field rule: source and destination CIDR
100, ..., 25600 random rules, prefixes are chosen from [8,24], TSS caps at 289=17^2

Problems with Tuple Space Search, IPv6



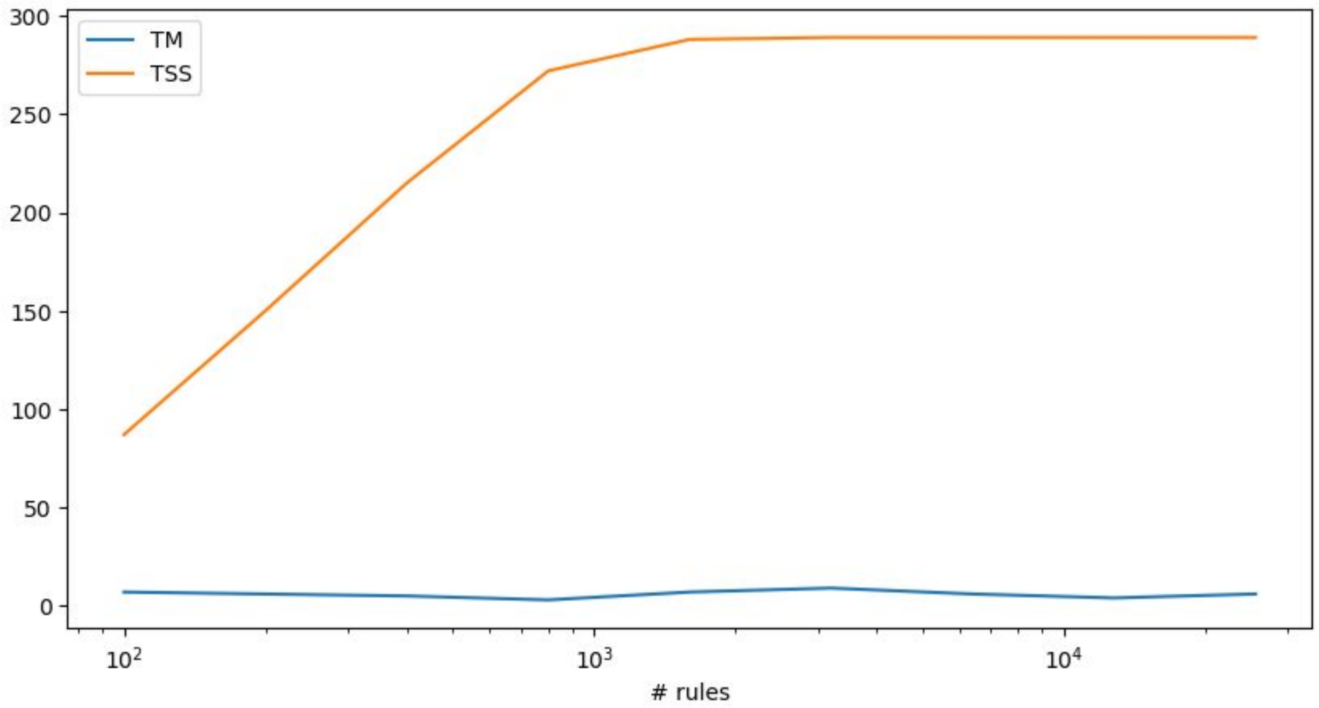
# of tables for TSS for two-field rule: source and destination CIDR
100, ..., 102400 random rules, prefixes are chosen from [32,96], TSS caps at 4225=65^2

Tuple Merge to save the day

- **Idea 1:** group rules not by exact prefix match, but if rule->prefix >= table->prefix
- Example: table T(16) fits
  - 192.168.0.0/**16** and 192.168.128.0/**17** and 10.1.1.0/**24** etc.
  - Doesn't match, say, 127.0.0.1/**8**

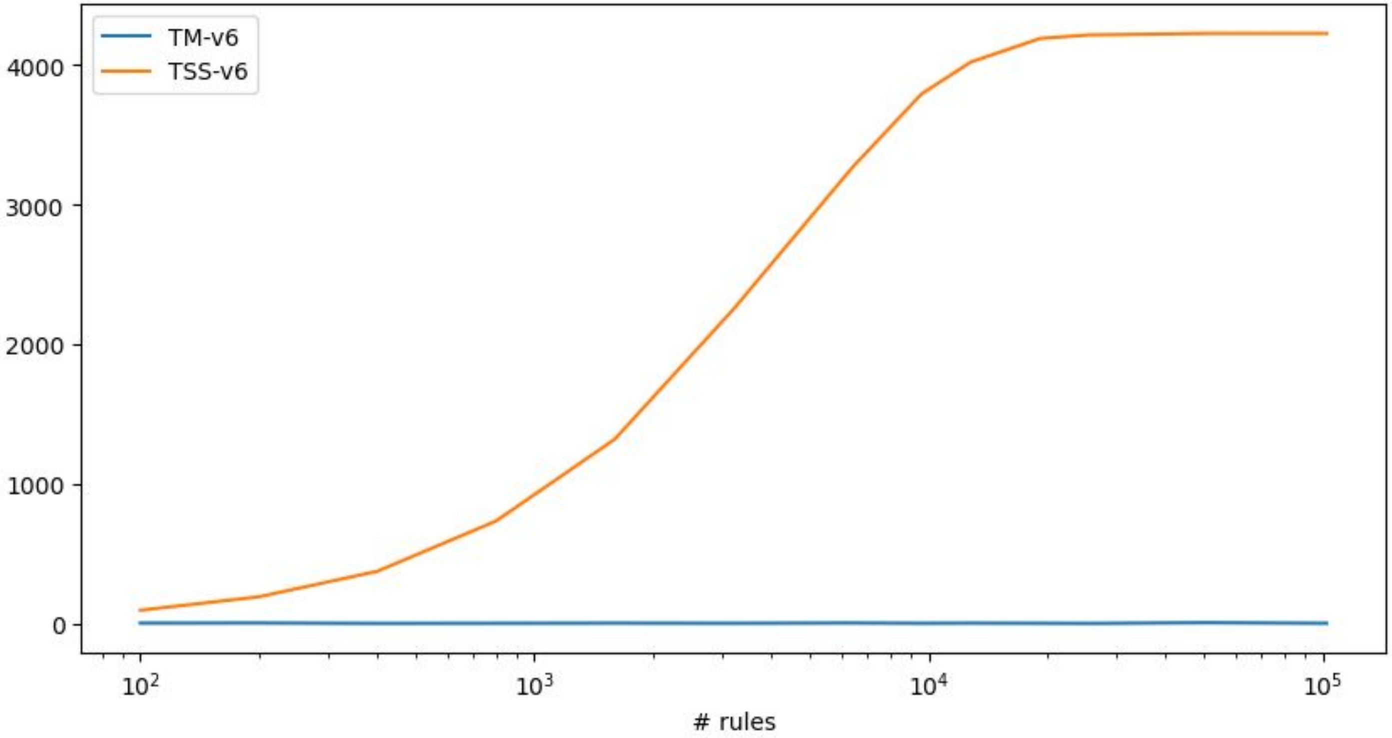
* See the whitepaper for more details: https://nonsns.github.io/paper/rossi19ton.pdf

Tuple Merge to save the day, IPv4



# of tables for two-field rule: source and destination CIDR, TSS (orange), TM (blue)
100, ..., 25600 random rules, prefixes are chosen from [8,24], TSS caps at 289=17^2

Tuple Merge to save the day, IPv6



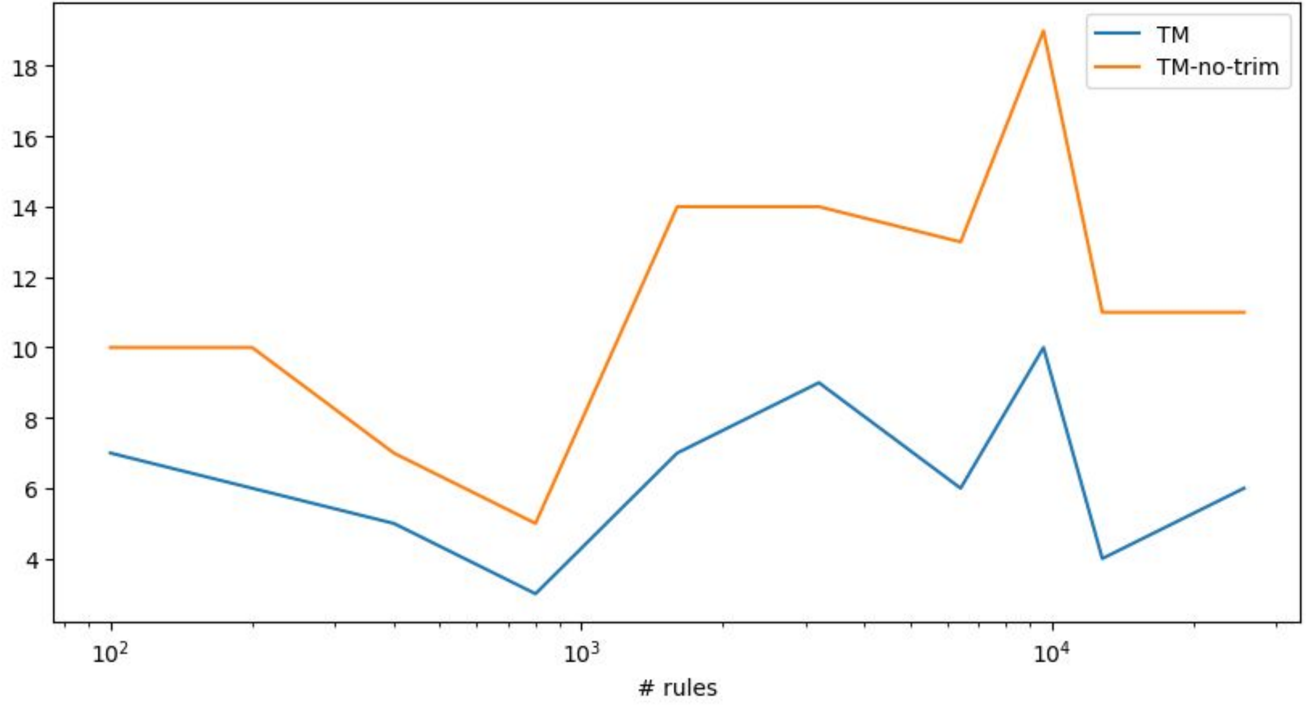
# of tables for two-field rule: source and destination CIDR, TSS (orange), TM (blue)
100, ..., 102400 random rules, prefixes are chosen from [32,96], TSS caps at 4225=65^2

Tuple Merge to save the day

- **Idea 2:** create new tables based on trimmed masks
- Example:
    - Got new rule 192.168.0.0**/16**
    - Create new table **/14** (= 16 - 16/8)
    - Next rule 172.17.0.0**/15** still fits

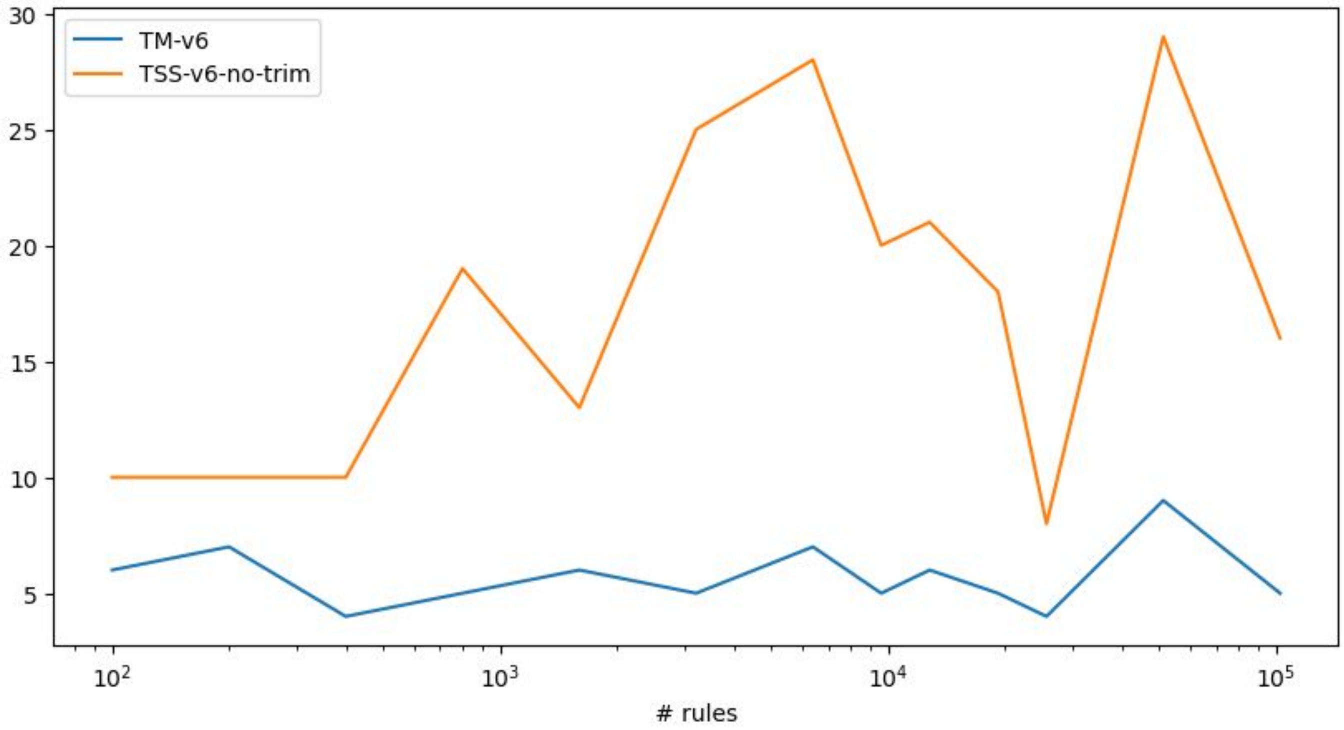
* See the whitepaper for more details: https://nonsns.github.io/paper/rossi19ton.pdf

Tuple Merge to save the day, IPv4



# of tables for TM with untrimmed tables (orange), TM (blue)
100, ..., 25600 random rules, prefixes are chosen from [8,24]

Tuple Merge to save the day, IPv6



# of tables for TM with untrimmed tables (orange), TM (blue)
100, ..., 102400 random rules, prefixes are chosen from [32,96]

Tuple Merge to save the day

- **Idea 3** (not implemented for the map): if we have table **(x, y)** where **y << x**, then convert it to **(x, 0)**, i.e., ignore y
- Example:
  - Rule: 192.168.0.0/**16**,192.168.2.0/**28**
  - New table **(14, 0)**

* See the whitepaper for more details: https://nonsns.github.io/paper/rossi19ton.pdf

Some Problems with Tuple Merge

- We can’t cap the number of tables
- The number of tables depends on the order in which rules appear, e.g.:
    - 10.0.0.0/8, 192.168.0.0/16 => **T(7)**
    - 192.168.0.0/16, 10.0.0.0/8 => **T(14),T(7)**

Static TM to save the day

- We can preallocate tables based on prior knowledge of rules structure
- E.g., for IPv6 4-tuples:
    - (**32, 32**, 0, 0), (**32, 0**, 0, 0), (**0, 32**, 0, 0)
- We will need only 1 hash computation*, and we still have 64 bits of randomness

---

* if no fields are ignored; e.g, a table (32,0,0,0) will be used if there are rules of form (ip/prefix, *, src-port-range, dst-port-range)

Problems with Static TM day

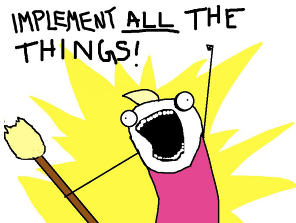
- Cast in Stone. Say, we’ve created a map with one table: (32,32,0,0), then we can’t ignore fields or add shorter
- Error-prone and bug-report-prone (users for sure *will* shoot themselves in the foot with this interface)

So, which algorithm to use?

So, which algorithm to use?

- Brute force:

  `BPF_WILDCARD_F_ALGORITHM_BF`

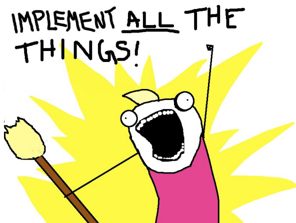


So, which algorithm to use?

- Brute force:

  `BPF_WILDCARD_F_ALGORITHM_BF`
- Tuple Merge:

  `BPF_WILDCARD_F_ALGORITHM_TM`



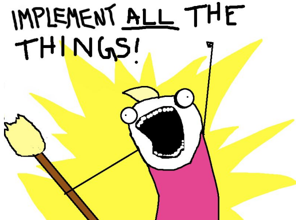
So, which algorithm to use?

- Brute force:

  `BPF_WILDCARD_F_ALGORITHM_BF`
- Tuple Merge:

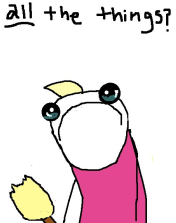
  `BPF_WILDCARD_F_ALGORITHM_TM`
- Static Tuple Merge:

  ```
  BPF_WILDCARD_F_ALGORITHM_TM |
  BPF_WILDCARD_F_TM_STATIC_POOL
  ```



So, which algorithm to use?

- Just choose the default algorithm
- Maybe provide some flags



Example: 4-tuple, wildcard

Four Fields:

Source IP/Prefix	(10.3.4.0/24)
Destination IP/Prefix	(192.168.0.0/16)
Source Port Range	(*)
Destination Port Range	(1-1024)

Allocate a map

```
BPF_WILDCARD_DESC_4(
    capture4_wcard,
    BPF_WILDCARD_RULE_PREFIX, __u32, saddr,
    BPF_WILDCARD_RULE_PREFIX, __u32, daddr,
    BPF_WILDCARD_RULE_RANGE, __u16, sport,
    BPF_WILDCARD_RULE_RANGE, __u16, dport
);

struct {
    __uint(type, BPF_MAP_TYPE_WILDCARD);
    __type(key, struct capture4_wcard_key);
    __type(value, __u64);
    __uint(max_entries, 100000);
    __uint(map_flags, BPF_F_NO_PREALLOC);
    __uint(map_extra, BPF_WILDCARD_F_ALGORITHM_TM);
    __type(wildcard_desc, struct capture4_wcard_desc);
} filter_v4_tm_dynamic __section(".maps");
```

Allocate a map

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BPF_WILDCARD_DESC_4(
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    BPF_WILDCARD_RULE_RANGE, __u16, sport,
    BPF_WILDCARD_RULE_RANGE, __u16, dport
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struct {
    __uint(type, BPF_MAP_TYPE_WILDCARD);
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    __type(wildcard_desc, struct capture4_wcard_desc);
} filter_v4_tm_dynamic __section(".maps");
```

Insert rules (userspace)

```
struct capture4_wcard_key rule = {

    .type = BPF_WILDCARD_KEY_RULE,

    .rule = {
        .saddr = pton("10.3.4.0"),
        .saddr_prefix = 24,
        .daddr = pton("192.168.0.0"),
        .daddr_prefix = 16,
        .sport_min = 0,
        .sport_max = 0xffff,
        .dport_min = 1,
        .dport_max = 1024,
    },
};

bpf_map_update_elem(fd, &rule, &val, 0);
```

Match packets (kernel space)

```
struct capture4_wcard_key key = {};

// … set up struct iphdr *ip4 and L4 *l4 …

key.type = BPF_WILDCARD_KEY_ELEM;
key.saddr = ip4->saddr;
key.daddr = ip4->daddr;
memcpy(&key.sport, l4, 4); /* copy both ports */

bpf_map_lookup_elem(&map, &key);
```

Define the rule structure

```
BPF_WILDCARD_DESC_4(
    capture4_wcard,
    BPF_WILDCARD_RULE_PREFIX, __u32, saddr,
    BPF_WILDCARD_RULE_PREFIX, __u32, daddr,
    BPF_WILDCARD_RULE_RANGE, __u16, sport,
    BPF_WILDCARD_RULE_RANGE, __u16, dport
);
```

Define the rule structure

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BPF_WILDCARD_DESC_4(
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BPF_WILDCARD_DESC_4(
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    BPF_WILDCARD_RULE_RANGE, __u16, dport
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Define the rule structure

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    BPF_WILDCARD_RULE_RANGE, __u16, sport,
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);
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    BPF_WILDCARD_RULE_RANGE, __u16, dport
);
```

Allocate a map

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    BPF_WILDCARD_RULE_PREFIX, __u32, daddr,
    BPF_WILDCARD_RULE_RANGE, __u16, sport,
    BPF_WILDCARD_RULE_RANGE, __u16, dport
);

struct {
    __uint(type, BPF_MAP_TYPE_WILDCARD);
    __type(key, struct capture4_wcard_key);
    __type(value, __u64);
    __uint(max_entries, 100000);
    __uint(map_flags, BPF_F_NO_PREALLOC);
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    __type(wildcard_desc, struct capture4_wcard_desc);
} filter_v4_tm_dynamic __section(".maps");
```

Map allocation

```
struct capture4_wcard_key {
        __u32 type;
        union {
                struct { /* rule */ };
                struct { /* packet */ };
        };
};

type is {BPF_WILDCARD_KEY_RULE,BPF_WILDCARD_KEY_ELEM}
```

Map allocation

```
struct capture4_wcard_key {
        __u32 type;
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        };
};

type is {BPF_WILDCARD_KEY_RULE,BPF_WILDCARD_KEY_ELEM}
```

Map allocation

Rule:

```
struct {
  __u32 saddr;
  __u32 saddr_prefix;
  __u32 daddr;
  __u32 daddr_prefix;
  __u16 sport_min;
  __u16 sport_max;
  __u16 dport_min;
  __u16 dport_max;
};
```

Packet:

```
struct {
    __u32 saddr;
    __u32 daddr;
    __u16 sport;
    __u16 dport;
};
```

Map allocation

Rule:

```
struct {
  __u32 saddr;
  __u32 saddr_prefix;
  __u32 daddr;
  __u32 daddr_prefix;
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  __u16 dport_min;
  __u16 dport_max;
};
```

Packet:

```
struct {
  __u32 saddr;
  __u32 daddr;
  __u16 sport;
  __u16 dport;
};
```

Map allocation

Rule:

```
struct {
   __u32 saddr;
   __u32 saddr_prefix;
   __u32 daddr;
   __u32 daddr_prefix;
   __u16 sport_min;
   __u16 sport_max;
   __u16 dport_min;
   __u16 dport_max;
};
```

Packet:

```
struct {
     __u32 saddr;
     __u32 daddr;
     __u16 sport;
     __u16 dport;
};
```

Map allocation

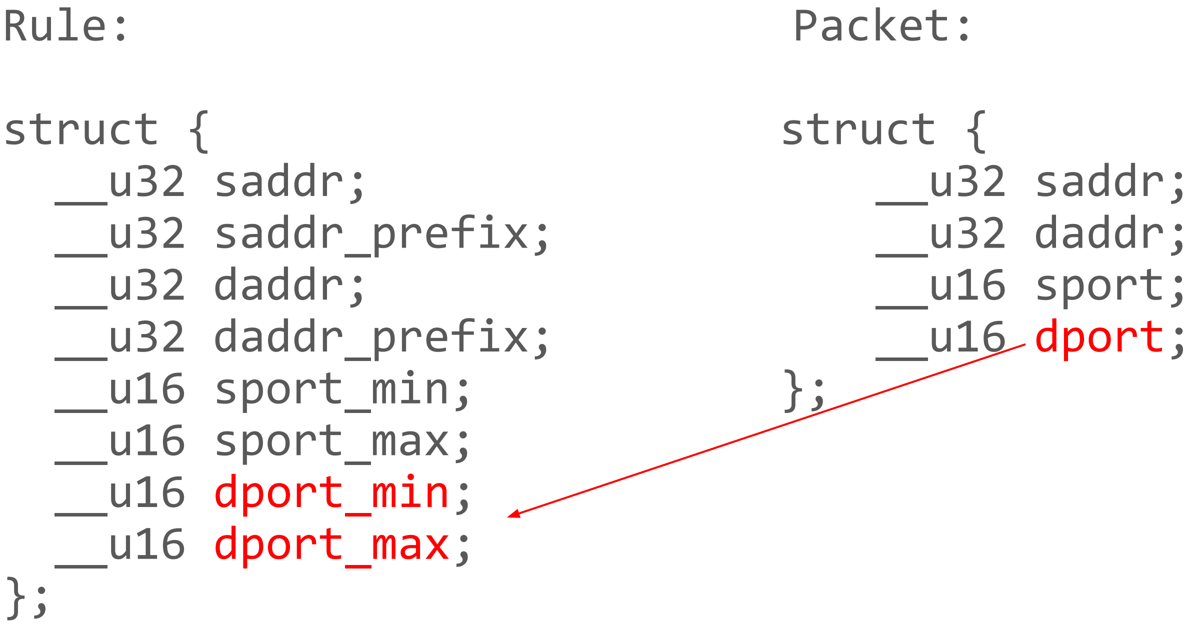
Rule:

```
struct {
  __u32 saddr;
  __u32 saddr_prefix;
  __u32 daddr;
  __u32 daddr_prefix;
  __u16 sport_min;
  __u16 sport_max;
  __u16 dport_min;
  __u16 dport_max;
};
```

Packet:

```
struct {
    __u32 saddr;
    __u32 daddr;
    __u16 sport;
    __u16 dport;
};
```

Map allocation



Rule:

```
struct {
  __u32 saddr;
  __u32 saddr_prefix;
  __u32 daddr;
  __u32 daddr_prefix;
  __u16 sport_min;
  __u16 sport_max;
  __u16 dport_min;
  __u16 dport_max;
};
```

Packet:

```
struct {
    __u32 saddr;
    __u32 daddr;
    __u16 sport;
    __u16 dport;
};
```

Map allocation, continued

- Users now know that this is a 4-tuple wildcard map
- But kernel will only see

```
void *key
map->key_size
```

Map allocation, continued

Tell kernel about the map structure:

```
struct wildcard_desc {
        __u32 n_rules;
        struct wildcard_rule_desc rule_desc[];
};

struct wildcard_rule_desc {
        __u32 type; /* WILDCARD_RULE_{PREFIX,RANGE,MATCH} */
        __u32 size; /* the size of the field in bytes */
        …
};
```

Map allocation, continued

Pass the following in bpf_attr:

```
struct wildcard_desc desc = {
        .n_rules = 4,
        .rule_desc = {
                { .type = BPF_WILDCARD_RULE_PREFIX, .size = 4, },
                { .type = BPF_WILDCARD_RULE_PREFIX, .size = 4, },
                { .type = BPF_WILDCARD_RULE_RANGE, .size = 2, },
                { .type = BPF_WILDCARD_RULE_RANGE, .size = 2, },
        },
};
```

Map allocation: here comes BTF

- We can’t just specify a `struct wildcard_desc` in a BTF map definition

- So, another structure is parsed by libbpf and converted to `wildcard_desc`

Map allocation, continued

```
struct capture4_wcard_desc {
    __uint(n_rules, 4);
    struct {
            __uint(type, BPF_WILDCARD_RULE_PREFIX);
            __uint(size, sizeof(__u32));
    } saddr;
    struct {
            __uint(type, BPF_WILDCARD_RULE_PREFIX);
            __uint(size, sizeof(__u32));
    } daddr;
    struct {
            __uint(type, BPF_WILDCARD_RULE_RANGE);
            __uint(size, sizeof(__u16));
    } sport;
    struct {
            __uint(type, BPF_WILDCARD_RULE_RANGE);
            __uint(size, sizeof(__u16));
    } dport;
};
```

Map allocation, continued

```
struct capture4_wcard_desc {
     __uint(n_rules, 4);
     struct {
               __uint(type, BPF_WILDCARD_RULE_PREFIX);
               __uint(size, sizeof(__u32));
     } saddr;
     struct {
               __uint(type, BPF_WILDCARD_RULE_PREFIX);
               __uint(size, sizeof(__u32));
     } daddr;
      ...
                             struct wildcard_desc desc = {
                                  .n_rules = 4,
                                  .rule_desc = {
                                       { .type = BPF_WILDCARD_RULE_PREFIX,.size = 4, },
                                       { .type = BPF_WILDCARD_RULE_PREFIX, .size = 4, },
                                       ...
```

Map allocation, continued

```
struct capture4_wcard_desc {
     __uint(n_rules, 4);
     struct {
               __uint(type, BPF_WILDCARD_RULE_PREFIX);
               __uint(size, sizeof(__u32));
     } saddr;
     struct {
               __uint(type, BPF_WILDCARD_RULE_PREFIX);
               __uint(size, sizeof(__u32));
     } daddr;
      ...
```

```
struct wildcard_desc desc = {
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          { .type = BPF_WILDCARD_RULE_PREFIX, .size = 4, },
          ...
```

Map allocation, continued

```
struct capture4_wcard_desc {
     __uint(n_rules, 4);
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               __uint(type, BPF_WILDCARD_RULE_PREFIX);
               __uint(size, sizeof(__u32));
     } saddr;
     struct {
               __uint(type, BPF_WILDCARD_RULE_PREFIX);
               __uint(size, sizeof(__u32));
     } daddr;
      ...
```

```
struct wildcard_desc desc = {
     .n_rules = 4,
     .rule_desc = {
          { .type = BPF_WILDCARD_RULE_PREFIX,.size = 4, },
          { .type = BPF_WILDCARD_RULE_PREFIX, .size = 4, },
          ...
```

Allocating maps is actually quite simple

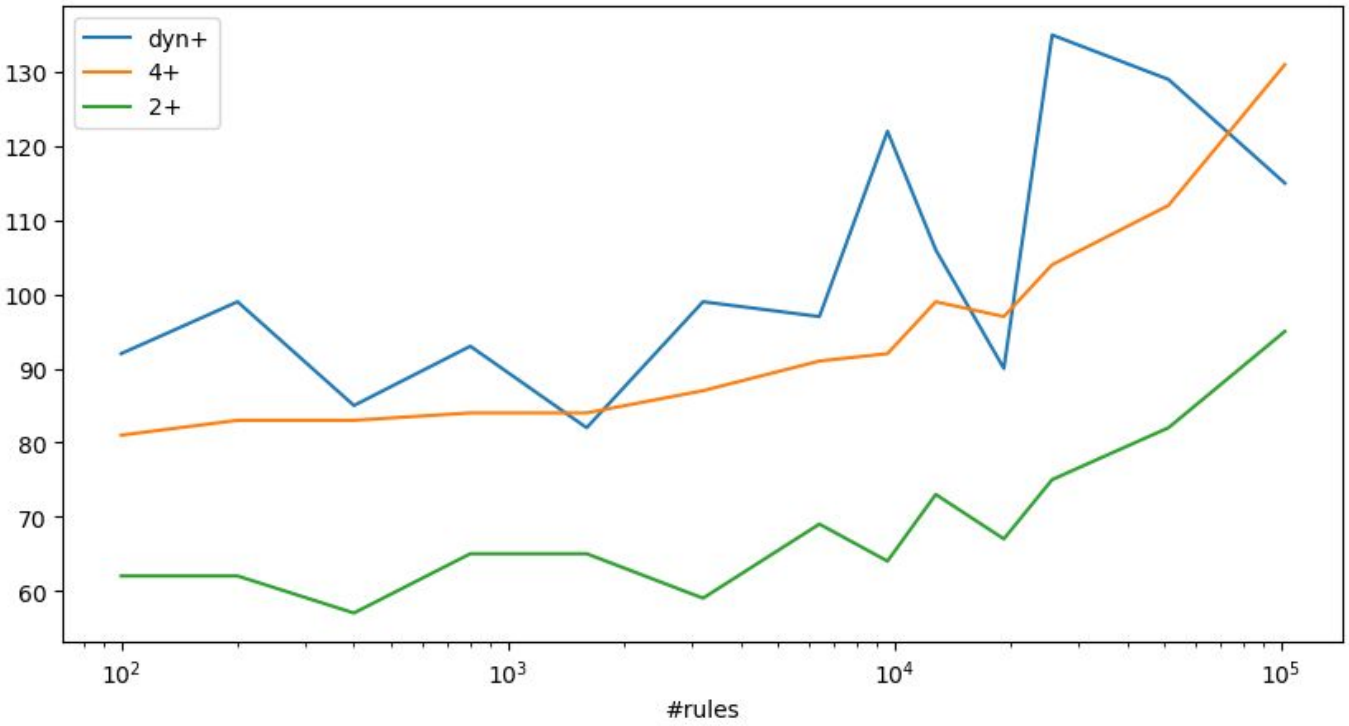
```
BPF_WILDCARD_DESC_4(
    capture4_wcard,
    BPF_WILDCARD_RULE_PREFIX, __u32, saddr,
    BPF_WILDCARD_RULE_PREFIX, __u32, daddr,
    BPF_WILDCARD_RULE_RANGE, __u16, sport,
    BPF_WILDCARD_RULE_RANGE, __u16, dport
);

struct {
    __uint(type, BPF_MAP_TYPE_WILDCARD);
    __type(key, struct capture4_wcard_key);
    __type(value, __u64);
    __uint(max_entries, 100000);
    __uint(map_flags, BPF_F_NO_PREALLOC);
    __uint(map_extra, BPF_WILDCARD_F_ALGORITHM_TM);
    __type(wildcard_desc, struct capture4_wcard_desc);
} filter_v4_tm_dynamic __section(".maps");
```

Kernel Changes Required

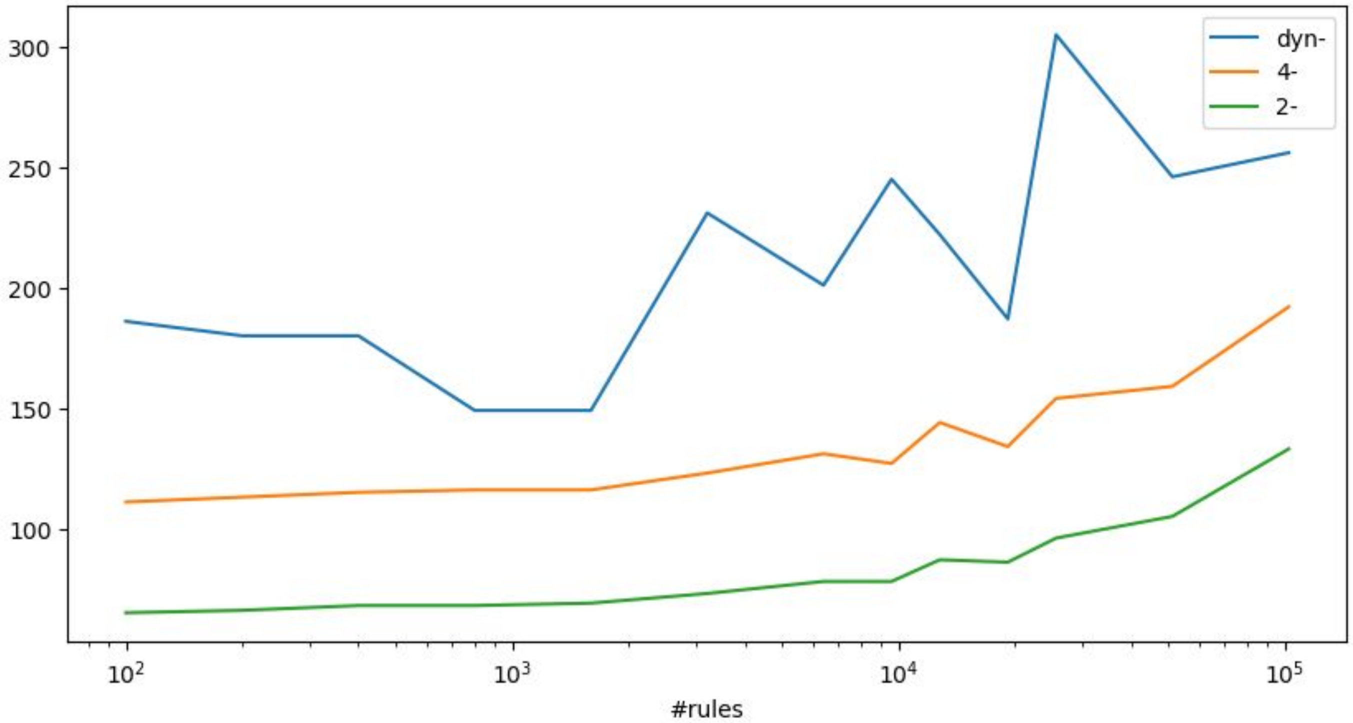
- **`bpf_attr:`** new fields, code to copy them:
  - **`void *map_extra_data`**
  - **`u32 map_extra_data_size`**
- Patch libbpf to parse new BTF definitions and pass data all the way to bpf(2)

Numbers: IPv4 4-tuple, TM, Static TM



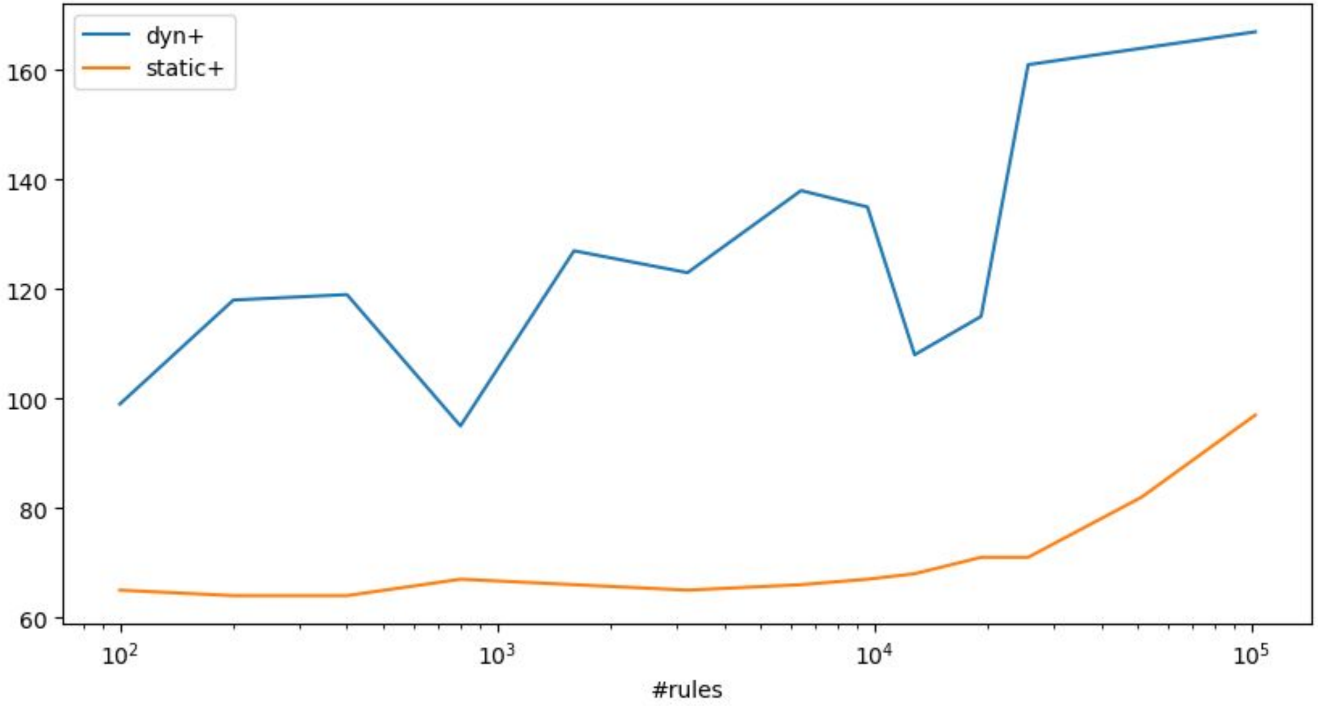
successful lookups, in nanoseconds, 100, ..., 102400 random rules, prefixes are chosen from [8,24]
dyn: generic Tuple Merge; 4: Static TM with tables=[(16,16),(16,8),(8,16),(8,8)]; 2: Static TM with tables=[(16,16),(8,8)]

Numbers: IPv4 4-tuple, TM, Static TM



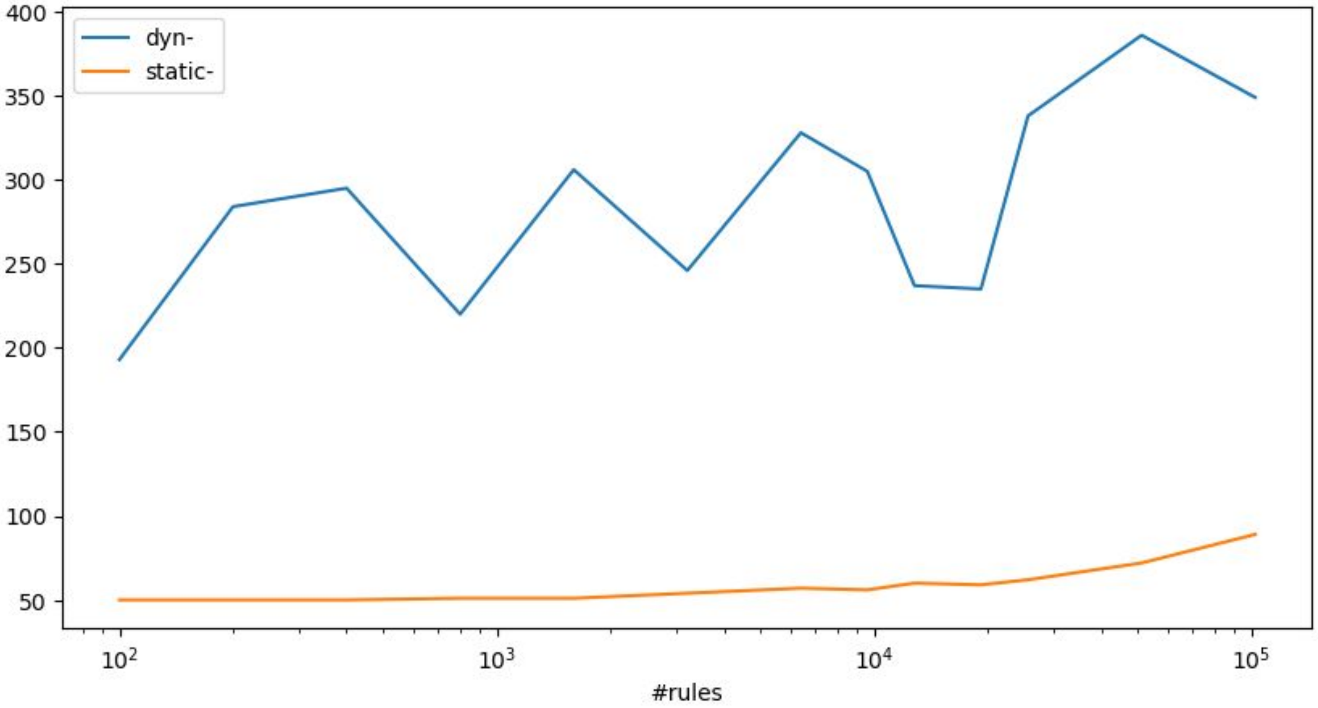
unsuccessful lookups, in nanoseconds, 100, ..., 102400 random rules, prefixes are chosen from [8,24]
dyn: generic Tuple Merge; 4: Static TM with tables=[(16,16),(16,8),(8,16),(8,8)]; 2: Static TM with tables=[(16,16),(8,8)]

Numbers: IPv6 4-tuple, TM, Static TM



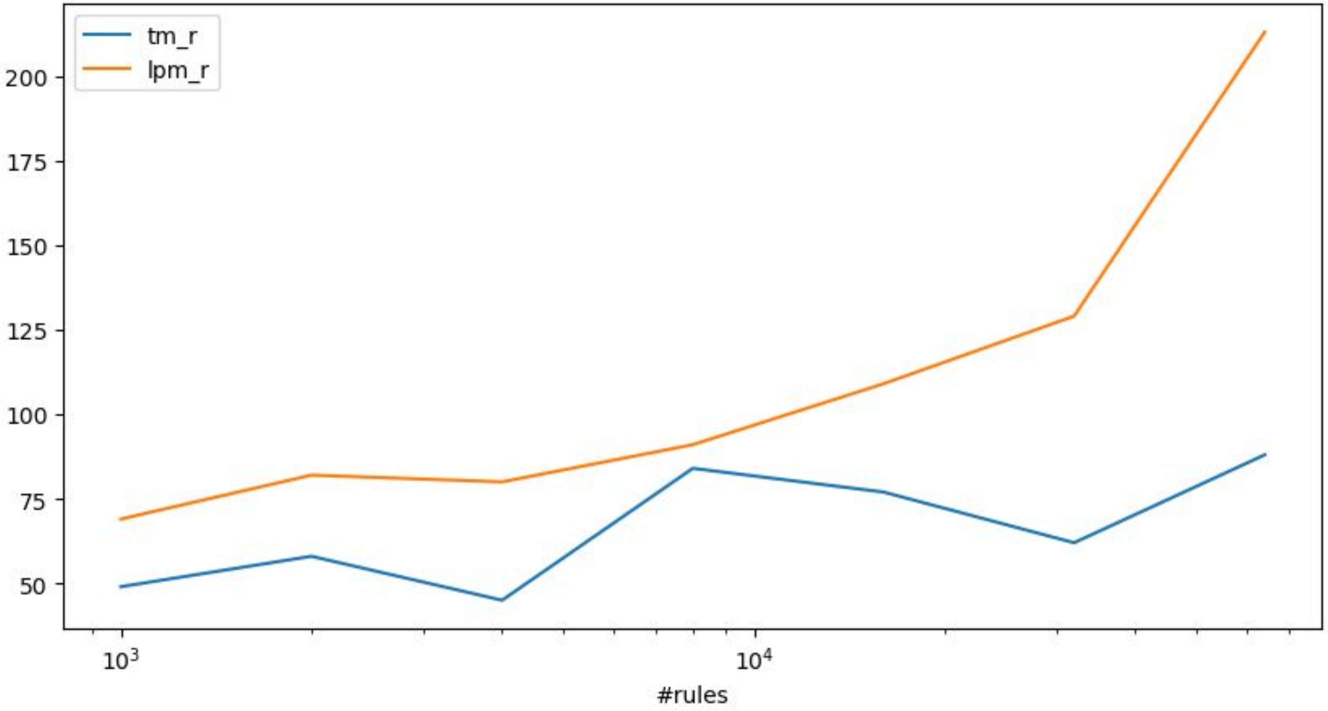
successful lookups, in nanoseconds, 100, ..., 102400 random rules, prefixes are chosen from [8,24]
dyn: generic Tuple Merge; static: Static TM with tables=[(32,32)]

Numbers: IPv6 4-tuple, TM, Static TM



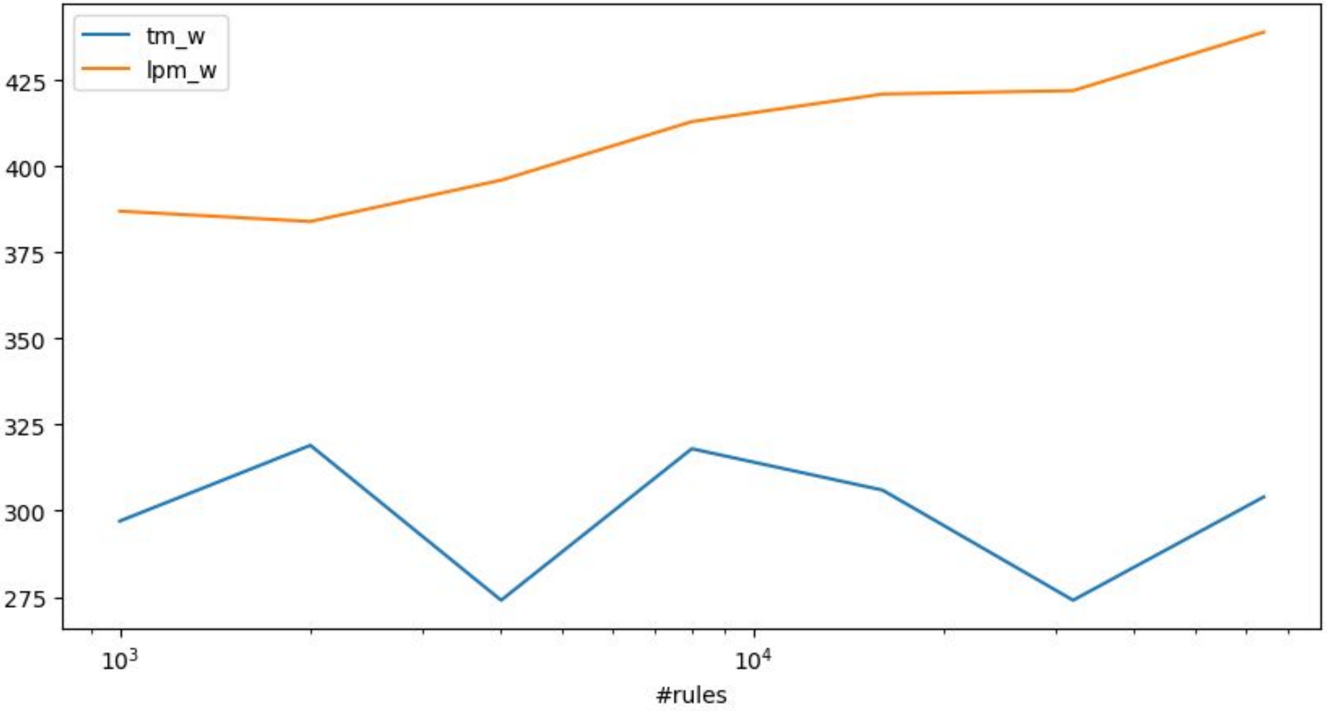
unsuccessful lookups, in nanoseconds, 100, ..., 102400 random rules, prefixes are chosen from [8,24]
dyn: generic Tuple Merge; static: Static TM with tables=[(32,32)]

Numbers: TM, LPM



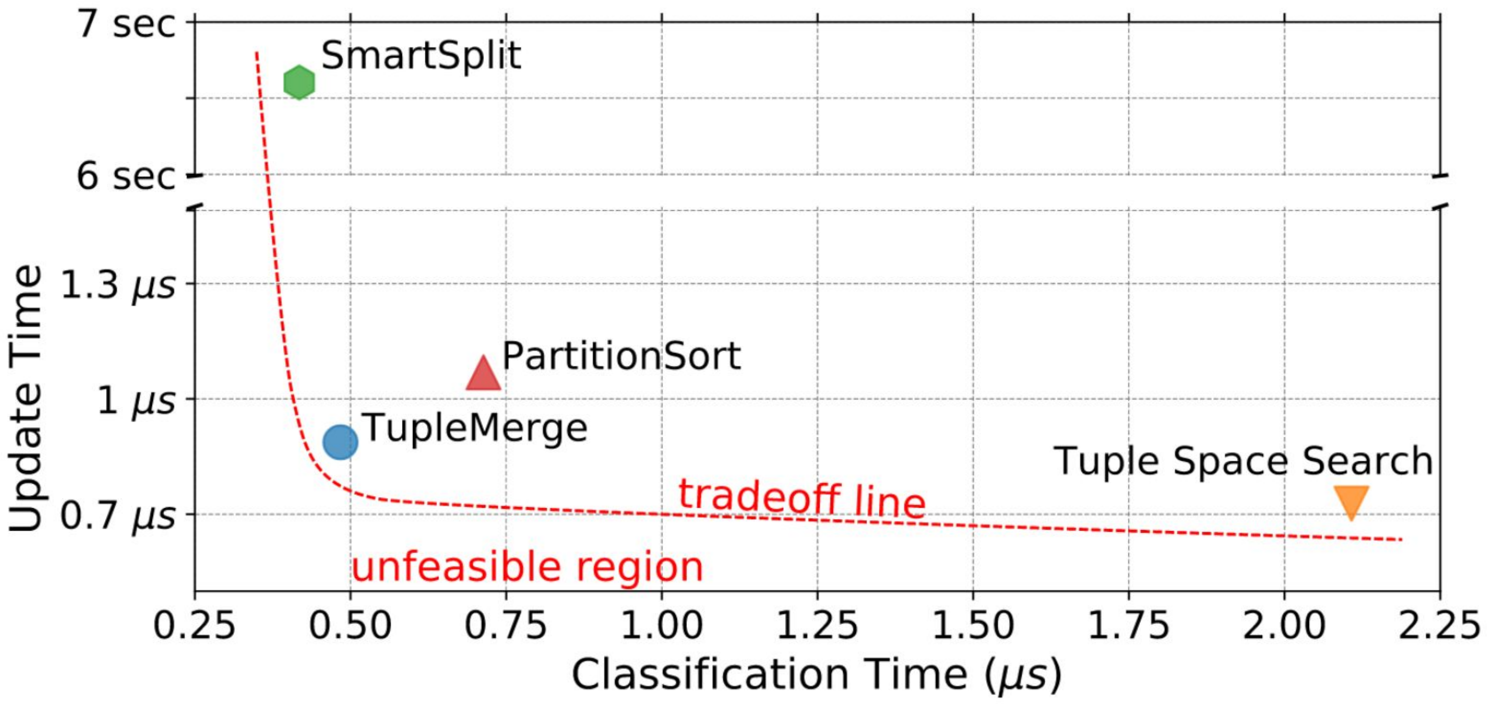
Successful lookups in nanoseconds, tm: Tuple Merge, trie: LPM trie
100,..., 64000 random IPv6 CIDRs, prefixes are random from /32 to /96

Numbers: TM, LPM



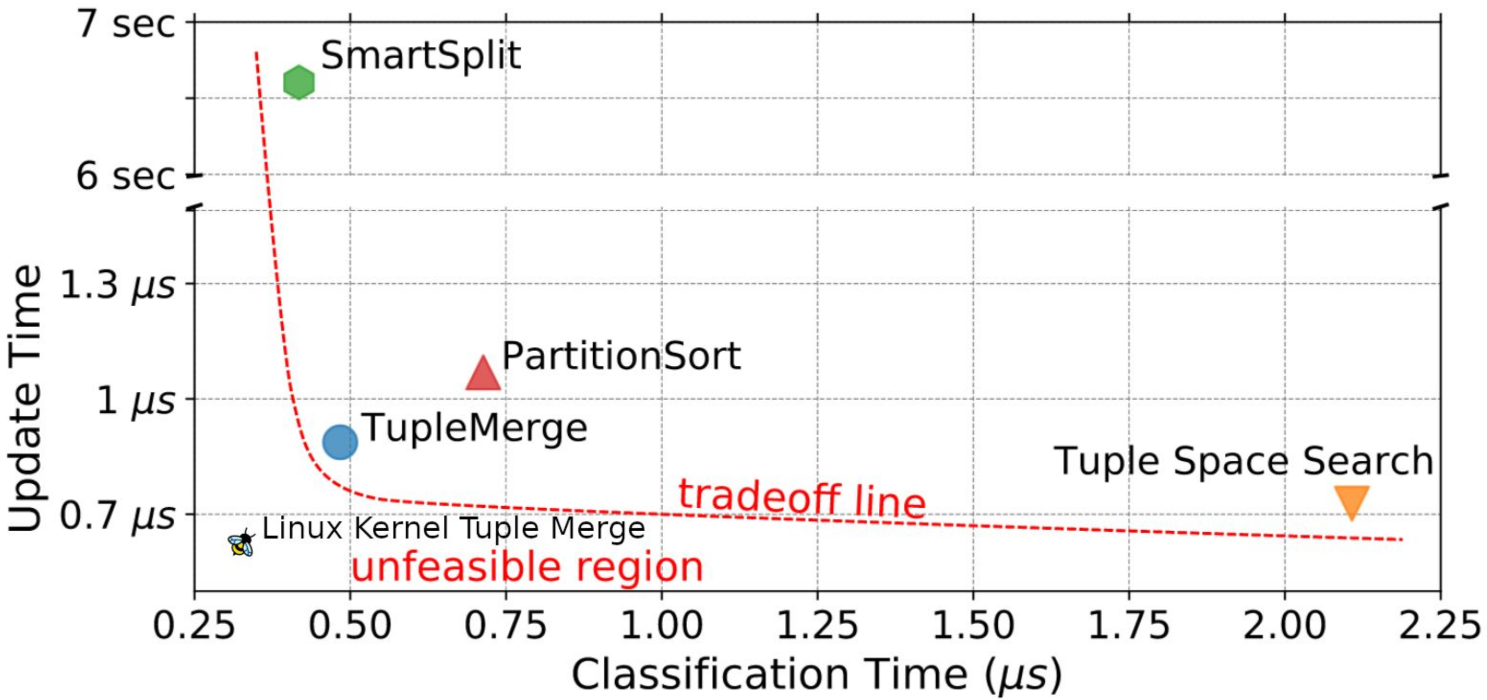
updates in nanoseconds, tm: Tuple Merge, trie: LPM trie
100,..., 64000 random IPv6 CIDRs, prefixes are random from /32 to /96

Existing Algorithms



* The picture is copied from [“TupleMerge: Fast Software Packet Processing for Online Packet Classification”]

Existing Algorithms, updated



* The picture is copied from "TupleMerge: Fast Software Packet Processing for Online Packet Classification"

Thanks! Questions, feedback, use cases?

- POC Code: [RFC patch]
- Please share your use cases!