SAX-PAC (Scalable And eXpressive PAcket Classification)

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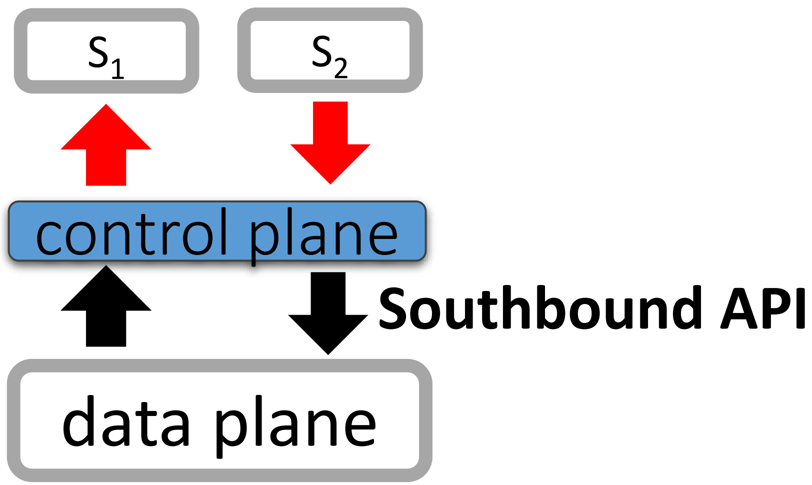
Outline

- Current state of the art in packet classification
- Impact of structural properties on representation efficiency
- Classifiers as Boolean expressions
- Proposed solutions
- Evaluation
- Summary and future work

Representation of expressiveness on data plane



$$
\begin{aligned}
R_1 &= ([1,3],[4,31],[1,28]) \\
R_2 &= ([4,4],[2,30],[4,27]) \\
R_3 &= ([7,9],[5,21],[3,18])
\end{aligned}
$$

priority

SW-based vs. TCAM-based solutions

SW-based: $N = 4$ rules $K = 2$ fields ~~prefixes~~ ~~ranges~~

$$
\begin{aligned}
R_1 &= (\; 100*, & 001* \;) \\
R_2 &= (\; 1010, & 0001 \;) \\
R_3 &= (\; 000*, & **** \;) \\
R_4 &= (\; 001*, & **** \;)
\end{aligned}
$$

Memory	Lookup time
$O(N)$	$O(log^{k-1}N)$
$O(N^k)$	$O(logN)$

TCAM-based: $N = 3$ rules $K = 3$ prefixes ~~ranges~~

$$
\begin{aligned}
R_1 &= ([1,3],[4,31],[1,28]) \\
R_2 &= ([4,4],[2,30],[4,27]) \\
R_3 &= ([7,9],[5,21],[3,18])
\end{aligned}
$$

Encoding	#TCAM entries
Binary	42+28+50=120
Gray	24+8+32=64

Order-independence

If the rules of a classifier do not ``intersect'', their order is not important.

$$\begin{aligned} R_1 &= ([1,3],[4,31],[1,28]) \\ R_2 &= ([4,4],[2,30],[4,27]) \\ R_3 &= ([7,9],[5,21],[3,18]) \end{aligned}$$

- Example: prefixes of the same length
- Implicit creation of order-dependence for service policies

	cisco1	cisco2	cisco3	fw	ipc	acl
Order-independent rules	120	249	329	39962	48294	49779
Total	148	269	364	45723	49840	49870
Order-independent %	81	93	90	87	97	99

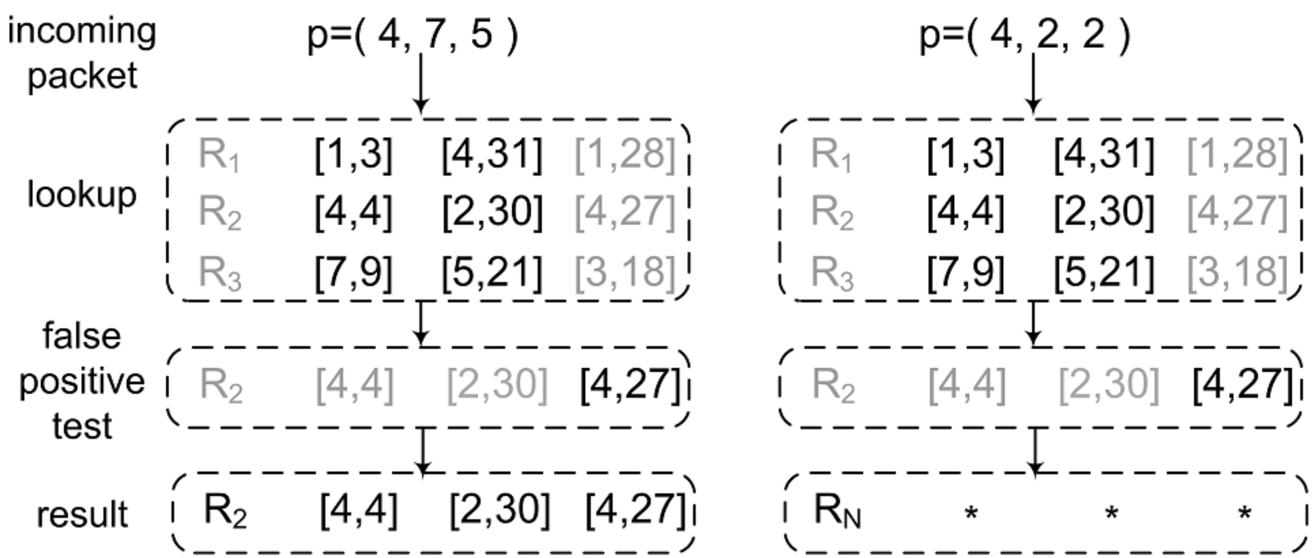
Exploiting order-independence

- Adding new fields keep order-independence
- At most one rule is matched and it can be false-positive
- We can reduce space by skipping new fields

$$
\begin{aligned}
R_1 &= ([1,3],[4,31]) \\
R_2 &= ([4,4],[2,30]) \\
R_3 &= ([7,9],[5,21])
\end{aligned}
$$

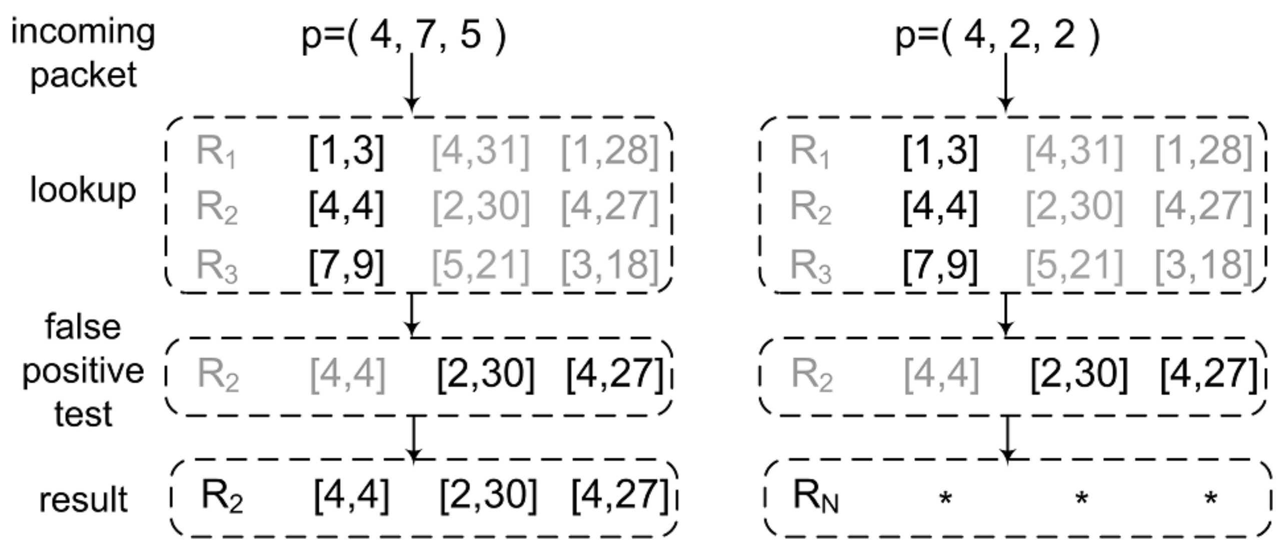
$$
\begin{aligned}
R_1^{+1} &= ([1,3],[4,31],[1,28]) \\
R_2^{+1} &= ([4,4],[2,30],[4,27]) \\
R_3^{+1} &= ([7,9],[5,21],[3,18])
\end{aligned}
$$

#Fields	Bin Encoding	Gray Encoding
2	6+7+10=23	6+4+8=18
3	42+28+50=120	24+8+32=64



Fields subset minimization (FSM)

Problem 1: Find a maximal subset M of fields of an order-independent classifier K s.t. K^{-M} is order-independent



Fields	Binary Encoding	Gray Encoding
{1,2,3}	42+28+50=120	24+8+32=64
{1,2}	6+7+10=23	6+4+8=18
{1}	2+1+2=5	2+1+2=5

Multi-group Representation

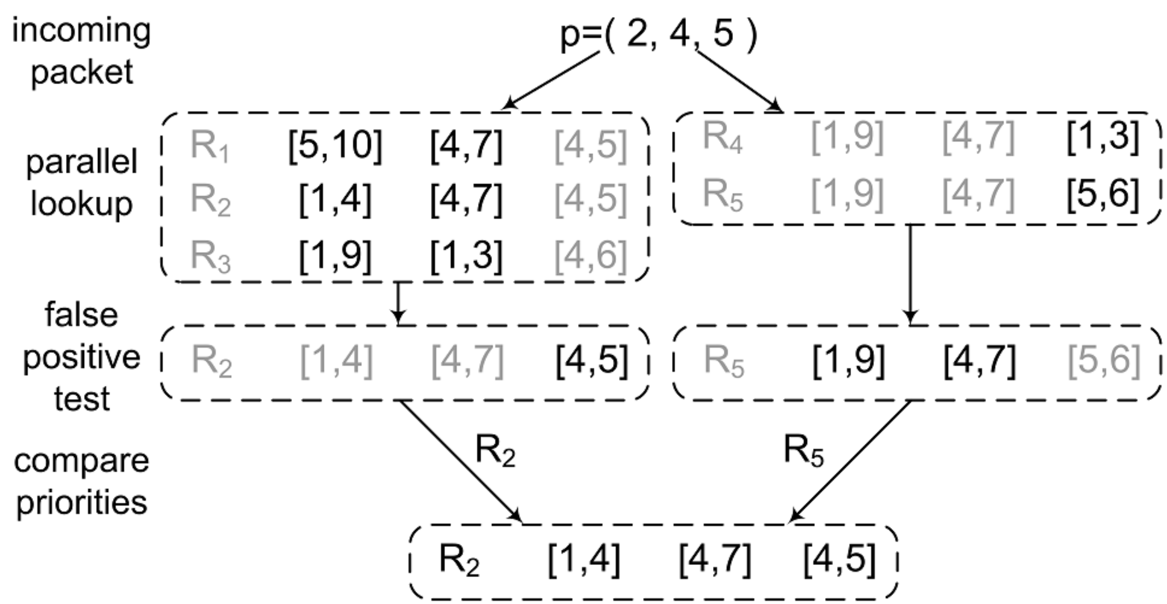
A classifier K is irreducible or order-dependent?

Problem 2: Given a classifier K on k fields and $0 < l < k$. Find an assignment of rules to a minimal number of disjoint groups s.t. every group is order-independent on l fields.

$$k = 3, l = 2$$

$$\begin{aligned} R_1 &= ([5,10],[4,7],[4,5]) \\ R_2 &= ([1,4],[4,7],[4,5]) \\ R_3 &= ([1,9],[1,3],[4,6]) \\ R_4 &= ([1,9],[4,7],[1,3]) \\ R_5 &= ([1,9],[4,7],[5,6]) \end{aligned}$$

$$R_1 \cap R_5 \neq \emptyset$$



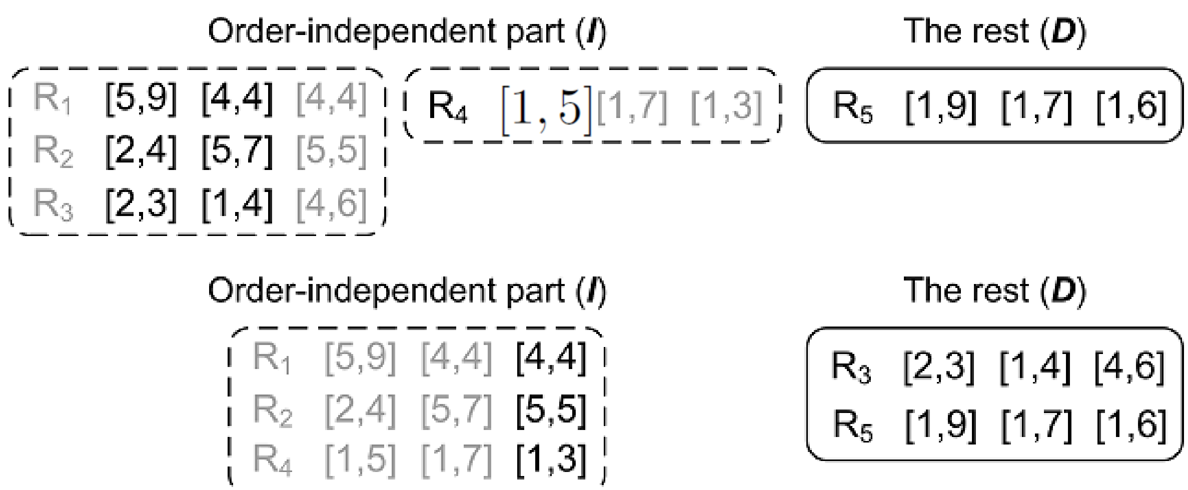
Multi-group representation of rules subset

Number of groups > supported level of parallelism β?

Problem 3: Given a classifier K on k fields, $0 < l < k$, and $\beta > 0$.
Find an assignment of a maximal subset of rules to β disjoint groups s.t. every group is order-independent on l fields.

$$k = 3, l = 2$$

$$\begin{aligned}
R_1 &= ([5,9],[4,4],[4,4]) \\
R_2 &= ([2,4],[5,7],[5,5]) \\
R_3 &= ([2,3],[1,4],[4,6]) \\
R_4 &= ([1,5],[1,7],[1,3]) \\
R_5 &= ([1,9],[1,7],[1,6])
\end{aligned}$$



$$\{R_1, R_2, R_3, R_4\}$$

Max order-independent set on 3 fields

Classifiers as Boolean expressions

$$
\begin{array}{rcllll}
R_1 & = & (& 100*, & 001* &) \\
R_2 & = & (& 1010, & 0001 &) \\
R_3 & = & (& 000*, & **** &) \\
R_4 & = & (& 001*, & **** &)
\end{array}
$$

$$
\begin{array}{l}
(x_1 \wedge \bar{x}_2 \wedge \bar{x}_3 \wedge \bar{x}_5 \wedge \bar{x}_6 \wedge x_7) \vee \\
(x_1 \wedge \bar{x}_2 \wedge x_3 \wedge \bar{x}_4 \wedge \bar{x}_5 \wedge \bar{x}_6 \wedge \bar{x}_7 \wedge x_8) \vee \\
(\bar{x}_1 \wedge \bar{x}_2 \wedge \bar{x}_3) \vee \\
(\bar{x}_1 \wedge \bar{x}_2 \wedge x_3)
\end{array}
$$

MinDNF: For a given Boolean function f, find a minimal size of DNF for f

MinDNF:

$$
\begin{array}{ll}
R_1 & = (100*, 001*) \\
R_2 & = (1010, 0001) \\
R_{34} & = (00**, ****)
\end{array}
$$

FSM with per field resolution:

$$
\begin{array}{lcl}
R_1^{-1} & = & (100*) \\
R_2^{-1} & = & (1010) \\
R_3^{-1} & = & (000*) \\
R_4^{-1} & = & (001*)
\end{array}
$$

FSM with per bit resolution:

$$
\begin{array}{lcl}
R_1^{-6} & = & (10) \\
R_2^{-6} & = & (11) \\
R_3^{-6} & = & (00) \\
R_4^{-6} & = & (01)
\end{array}
$$

Exact algorithm

FSM is NPC (reduction from SetCover)

Algorithm FSMBinSearch(k, min, max)

$m = \lfloor \frac{min+max}{2} \rfloor$
if $min = max$ **then return** m
for $M \subseteq \{1, \ldots, k\}, |M| = m$ **do**
    if IsOrderIndependent(M) **then**
        $min = m$
        return FSMBinSearch(k, min, max)
$max = m - 1$
return FSMBinSearch(k, min, max)

Theorem: $FSMBinSearch(k, 0, k-1)$ runs in time $O(k2^{k-1}N^2)$

Approximate algorithms

$$\begin{array}{llll} & S_1 & S_2 & S_3 \\ R_1 & = ([1,3], & [4,31], & [1,28]) \\ R_2 & = ([4,4], & [2,30], & [4,27]) \\ R_3 & = ([7,9], & [5,21], & [28,31]) \end{array}$$

Heuristics: algorithms for $SetCover$ and $MaxSetCoverage$

$$U = \{(i,j) | i < j, i,j \in [1,N]\} = \{(1,2),(1,3),(2,3)\}$$

Define $k\ sets\ S_1, .., S_k$ (one per field) to cover U
$S_i, 1 \leq i \leq k$, contains all pairs of rules that do not intersect in this field

$$S_1 = \{(1,2),(1,3),(2,3)\}\ S_2 = \emptyset\ S_3 = \{(2,3)\}$$

Theorem: FSM is reducible to $SetCover$ in $O(kN^2)$ time with approximation factor $2\ln(N) + 1$

Evaluation

6 classifiers with real parameters (see paper for more examples)

#		Max OI part 5 fields			Multi-group representation									
	Total				1-field groups					2-field groups				
	rules	OI size	FSM	{0,1}	all	95%	99%	≤ 2	≤ 5	all	95%	99%	≤ 2	≤ 5
1	584	538	0,1,3,4	406	15	8	13	2	8	10	4	7	3	4
2	269	249	0,1,4	246	4	2	3	1	1	2	2	2	0	0
3	364	329	0,1,3,4	324	7	3	5	2	4	4	2	3	1	14
4	49870	49779	0,1,4	49768	16	1	1	6	9	12	1	1	5	7
5	47276	44178	0,1,3,4	43819	67	5	13	19	32	39	2	5	10	20
6	48885	48826	0,1,2,4	48755	20	3	3	15	15	12	1	1	5	9

Summary

- Semantically equivalent: more fields imply less efficient representation
- Representation with false-positive: more fields – more efficient representation
- Structural properties can significantly improve time-space trade-off
- No restrictions on representation of every group (we define only additional abstraction layer)

Ongoing and future work

- Consider special cases as a FIB representation

G. Retvari et al., **Compressing IP Forwarding Tables: Towards Entropy Bounds and Beyond** SIGCOMM 13

- Identify additional structural properties
- Composition of structural properties
- Application to neighboring fields: data bases, program optimization, etc.

Thank you