Packet Classification: From Theory to Practice

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Most contributions from Yaxuan Qi and many other students of mine

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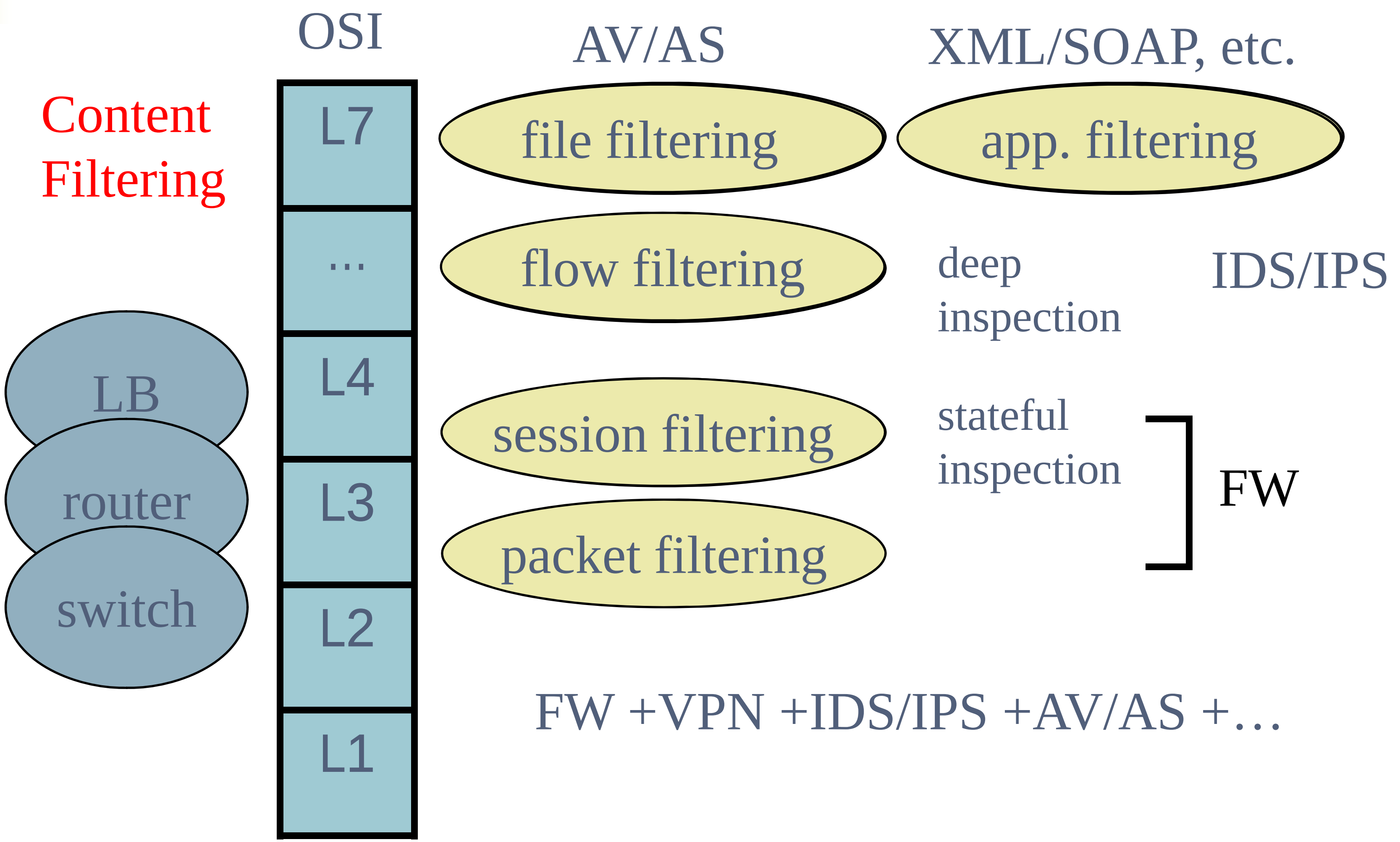
Outline

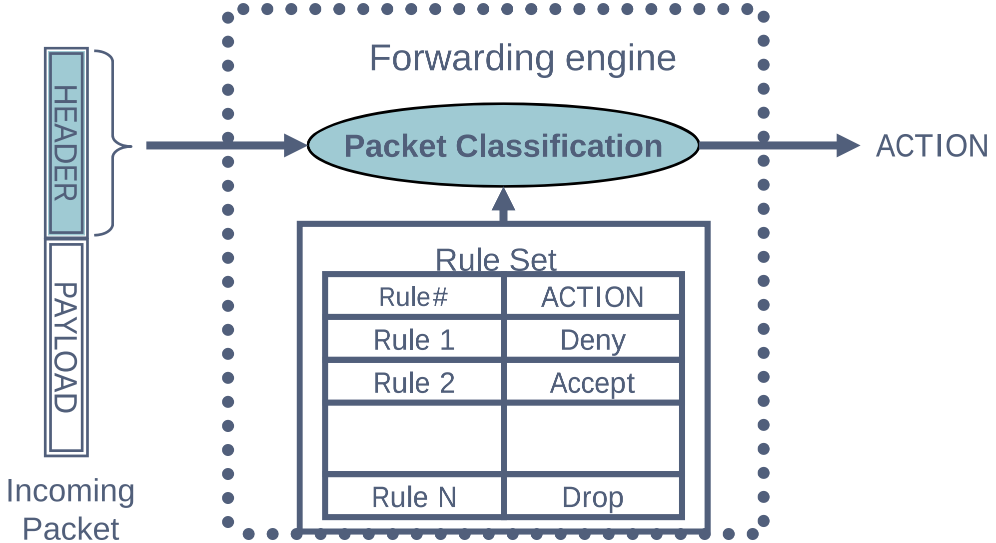
- Packet Classification Introduction
- Review of Classic Algorithms
- Our Recent Advancement
- Conclusion and Discussion

Network Security Gateway



The Packet Classification Problem

- Definition:
  - Given *N* rules, find the action associated with the highest priority rule matching an incoming packet.
- Applications:
  - Access control
  - Quality of service
  - Traffic engineering
  - Intrusion detection
  - …



	Field 1 (sIP)	Field 2 (dPort)	...	Field F (protocol)	Action
Rule 1	166.111.72.50/21	80	...	UDP	Deny
Rule 2	166.168.3.0/24	53	...	TCP	Accept
...	...	...	...	...	...
Rule N	0.0.0.0/0	0~65535	...	ANY	Drop

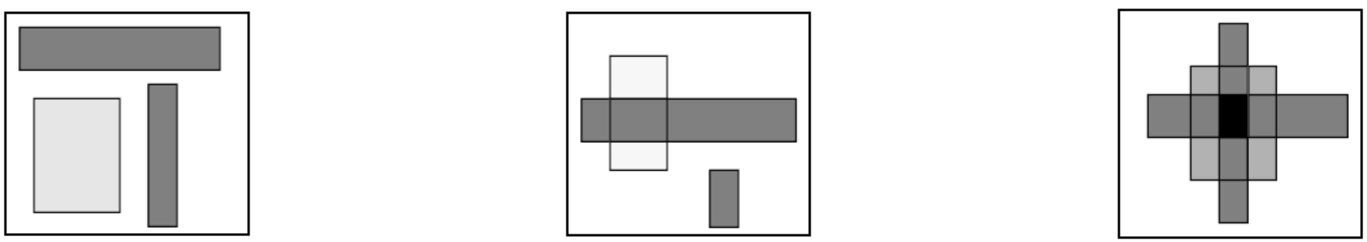
Problem Definition I

- Given a classifier C with N rules, R_j, $1 \leq j \leq N$, where R_j consists of three entities:
  - **Range expressions:** $R_j[i]$, $1 \leq i \leq d$, on each of the d header fields.
  - **Priority:** pri(R_j), indicating the priority of the rule in the classifier. Commonly, 1^{st} policy has the highest priority, N^{th} policy (normally deny all) has the lowest.
  - **An action:** referred to as action(R_j). In firewall, usually there is a default policy as the last policy that matches and denies all.

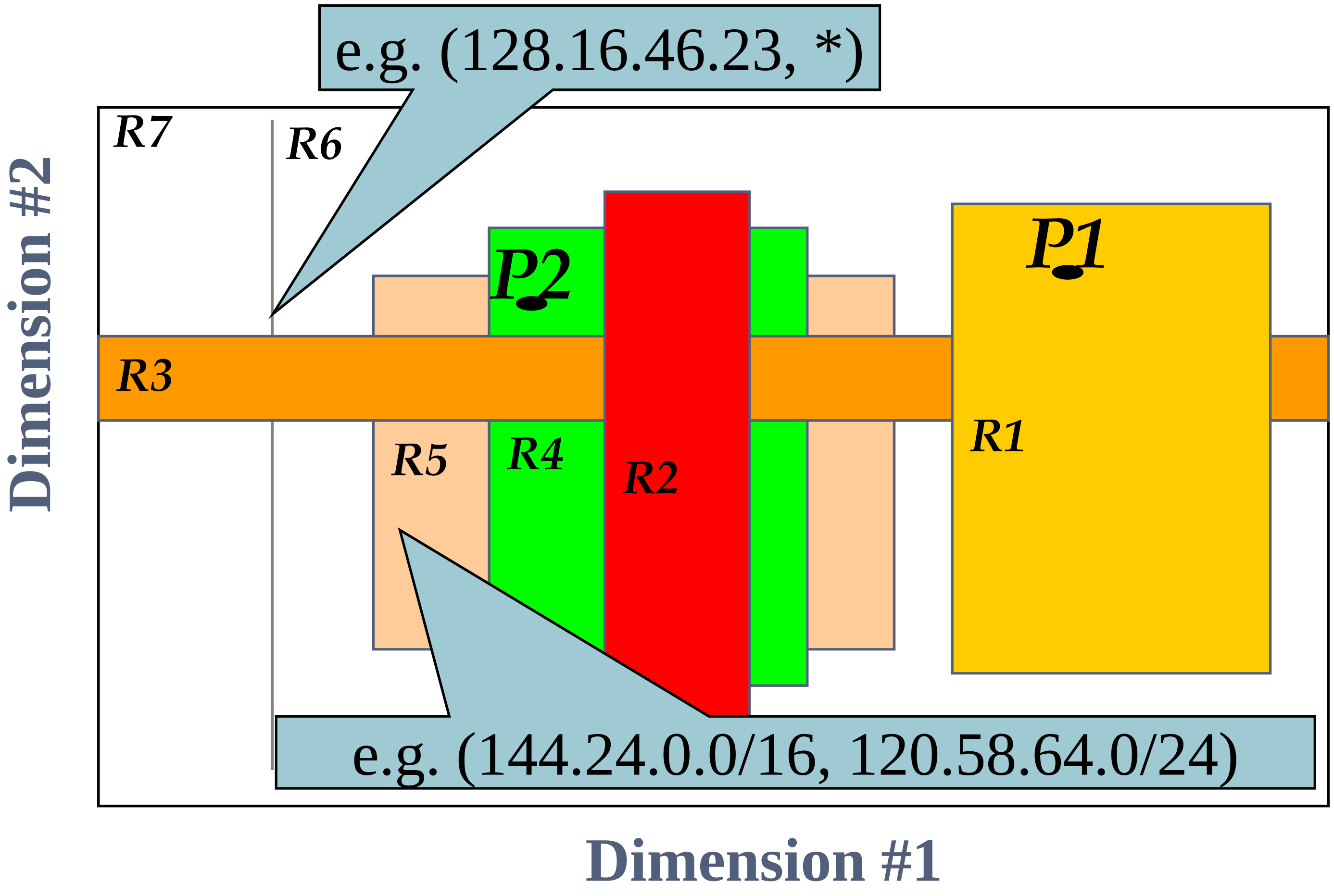
Problem Definition II

- For an incoming packet P with the header considered as a d-tuple of points (P_1, P_2, …, P_d), the *d-dimensional packet classification problem* is to find the rule R_m with the highest priority among all the N rules that match the d-tuple
  - i.e., pri(R_m) > pri(R_j), $\forall j \neq m, 1 \leq j \leq N$, such that P_i matches $R_j[i]$, $1 \leq i \leq d$. In firewall, this is the first matching policy.
  - R_m is called the best matching rule for packet P, therefore action(R_m) is applied to packet P.

Problem Complexity: Theoretically

- Computational Geometry
  - Point Location among N non-overlapping hyper-rectangles in F dimensions
  - Takes either $O(\log N)$ time with $O(N^F)$ space or $O(N)$ space with $O(\log^{F-1} N)$ time
  - E.g. N=1000, F=4: 1000G memory or 1000 times access
  - 
- De-overlapping
  - Each field need up to (2N-1) non-overlapping regions to represent N rules. How about F fields?
- Range-to-Prefix
  - Each rule with ranges in [0, 2^W-1] becomes up to $(2W-2)^F$ rules. How about N rules?

Geometric Interpretation in 2D



Problem Complexity: Practically

TABLE I. THEORETICAL VS. PRACTICAL COMPLEXITY FOR REAL-LIFE RULES

Rule Sets	*# rules*	*# non-over ranges in each field (theoretical)*	*# non-over ranges in sIP (practical)*	*# non-over ranges in dIP (practical)*	*# non-over ranges in sPT (practical)*	*# non-over ranges in dPT (practical)*	*# non-over rectangles (theoretical)*	*# non-over rectangles (practical)*
FW1	269	539	100	111	23	77	8.44×10^{10}	1.97×10^{7}
FW1-100	92	185	19	45	20	48	1.17×10^{9}	8.21×10^{5}
FW1-1K	791	1583	221	314	23	75	6.28×10^{12}	1.20×10^{8}
FW1-5K	4653	9307	3429	5251	23	77	7.50×10^{15}	3.19×10^{10}
FW1-10K	9311	18623	[illegible]	[illegible]	[illegible]	[illegible]	1.20×10^{17}	1.71×10^{11}
ACL1	752	1505	[illegible]	[illegible]	[illegible]	[illegible]	5.13×10^{12}	9.67×10^{6}
ACL1-100	98	197	[illegible]	[illegible]	[illegible]	[illegible]	1.51×10^{9}	4.03×10^{5}
ACL1-1K	916	1833	[illegible]	[illegible]	[illegible]	[illegible]	1.13×10^{13}	1.32×10^{7}
ACL1-5K	4415	8831	[illegible]	[illegible]	[illegible]	[illegible]	6.08×10^{15}	2.42×10^{8}
ACL1-10K	9603	19207	[illegible]	[illegible]	[illegible]	[illegible]	1.36×10^{17}	1.90×10^{9}
IPC1	1550	3101	[illegible]	[illegible]	[illegible]	[illegible]	9.25×10^{13}	3.40×10^{8}
IPC1-100	99	199	[illegible]	[illegible]	[illegible]	[illegible]	1.57×10^{9}	9.49×10^{6}
IPC1-1K	938	1877	[illegible]	[illegible]	[illegible]	[illegible]	1.24×10^{13}	1.70×10^{9}
IPC1-5K	4460	8921	886	2125	59	93	6.33×10^{15}	1.03×10^{10}
IPC1-10K	9037	18075	2377	4604	59	94	1.07×10^{17}	6.07×10^{10}

Note: sIP, dIP, sPT and dPT are source IP, destination IP, source Port and destination Port; FW, ACL, IPC are firewall policies, access control lists, and IP chain rules

worst-case: $5.13\text{x}10^{12}$
practical: $9.67\text{x}10^{6}$

- Fortunately
  - Few application reaches the worst case bound
  - Real-life rule sets have some inherent data-structures

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Existing Work: Basic Ideas

- Divide-and-Conquer
  - **Space Decomposition**
    - Decompose the search space into multiple sub-spaces using a set of axis-orthogonal hyper-planes. Each sub-space is associated with a sub-set of rules.
  - **Recursion Scheme**
    - Recursively apply the space decomposition, the original problem is divided into a series of sub-problems with smaller search space and fewer rules.

Example Rule Set

2-field rules with overlap

R1 has the highest priority

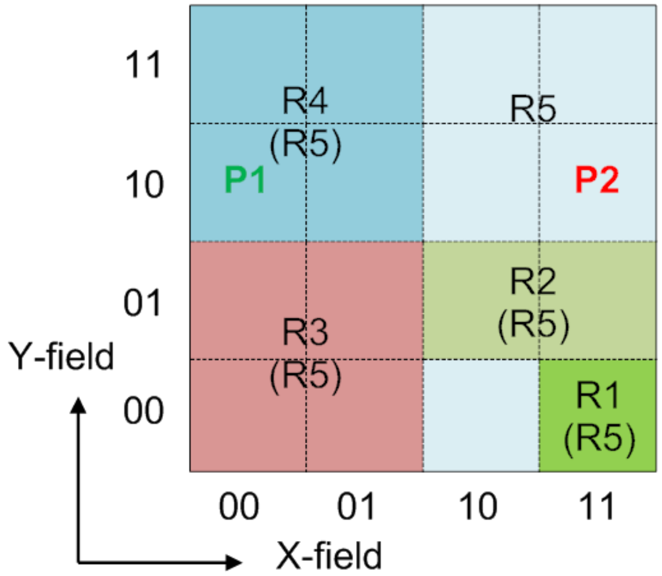
R5 is the default rule

2 Points

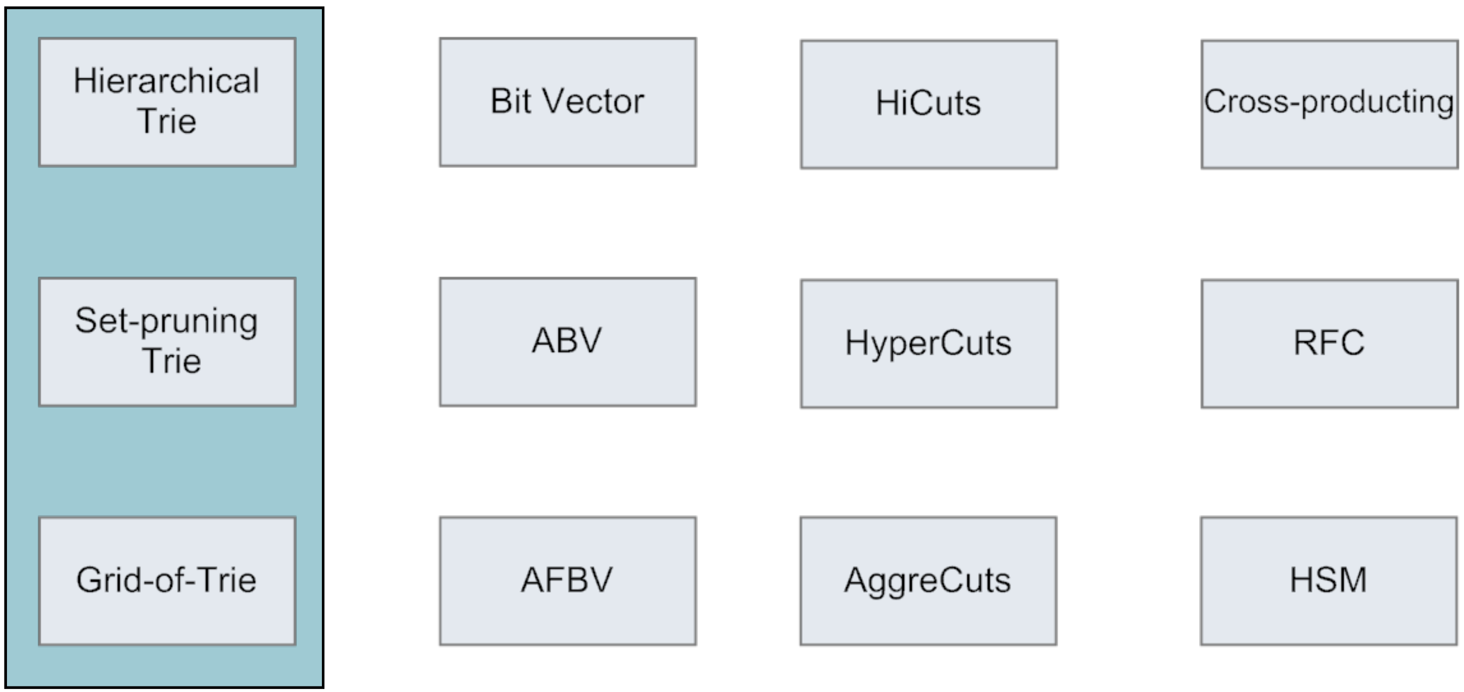
P1: (00, 10) → R4

P2: (11, 10) → R5

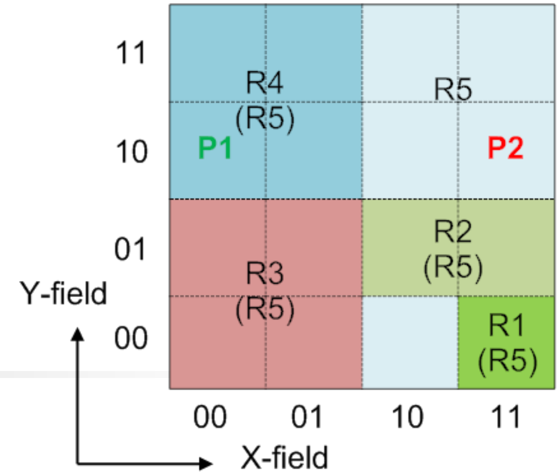
	X-field	Y-field
R1	11	00
R2	1*	01
R3	0*	0*
R4	0*	1*
R5	*	*

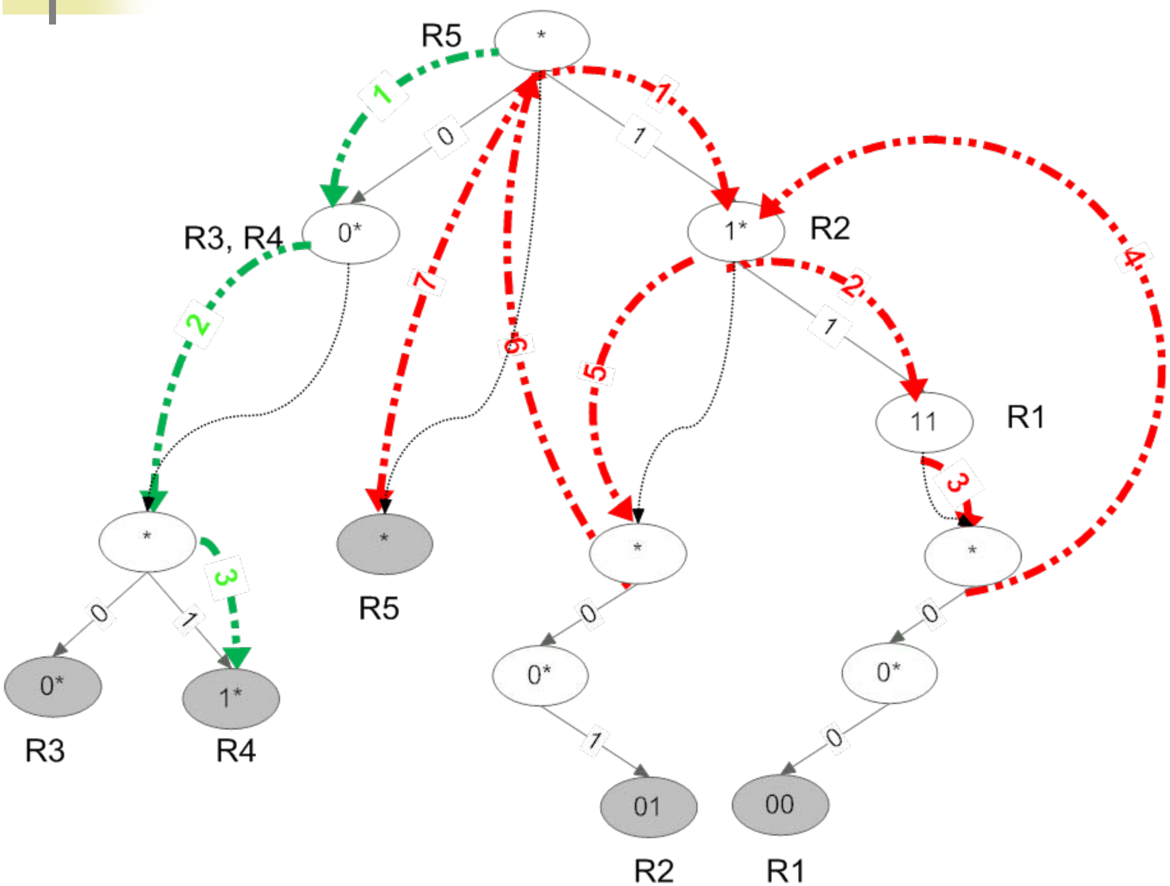


Packet Classification Algorithms



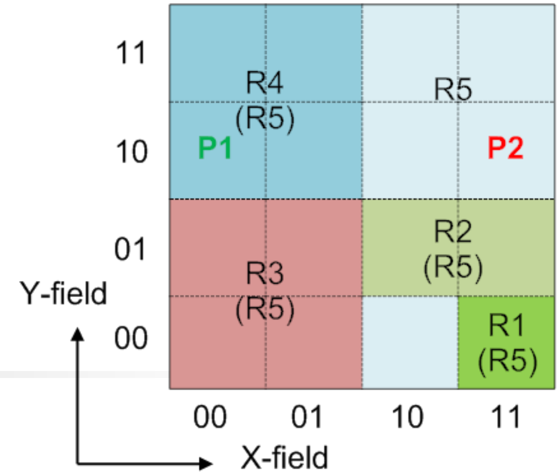
Hierarchical Tries

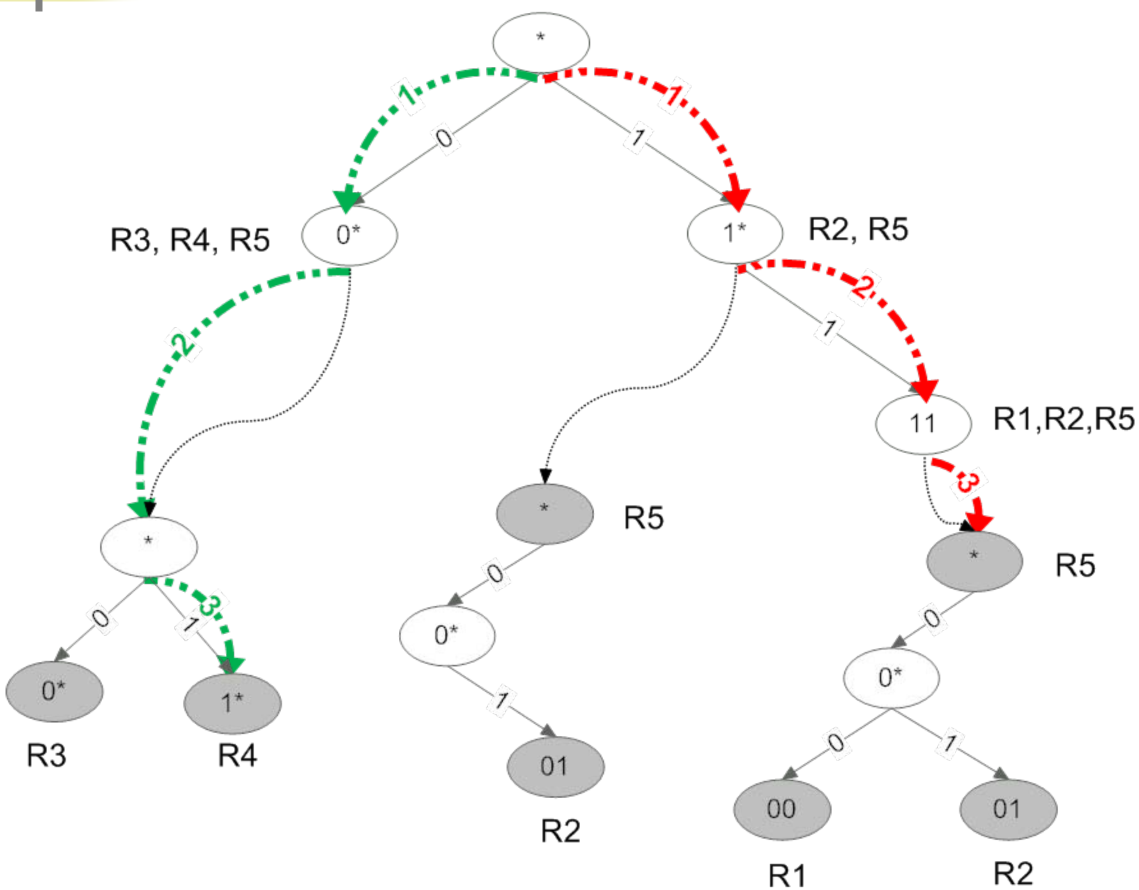




- Back-tracking search: O(Wd) time
- Each rule appears only once: O(N) space

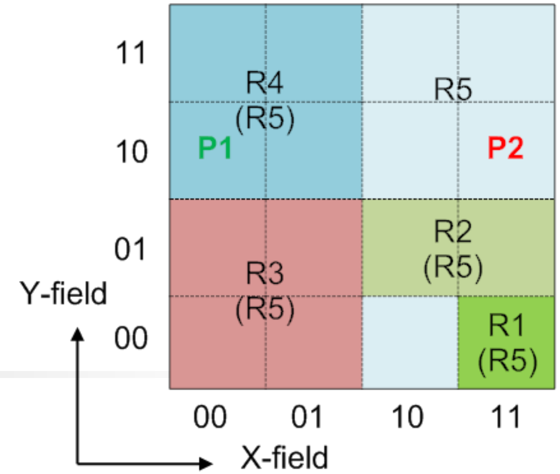
Set-pruning Tries

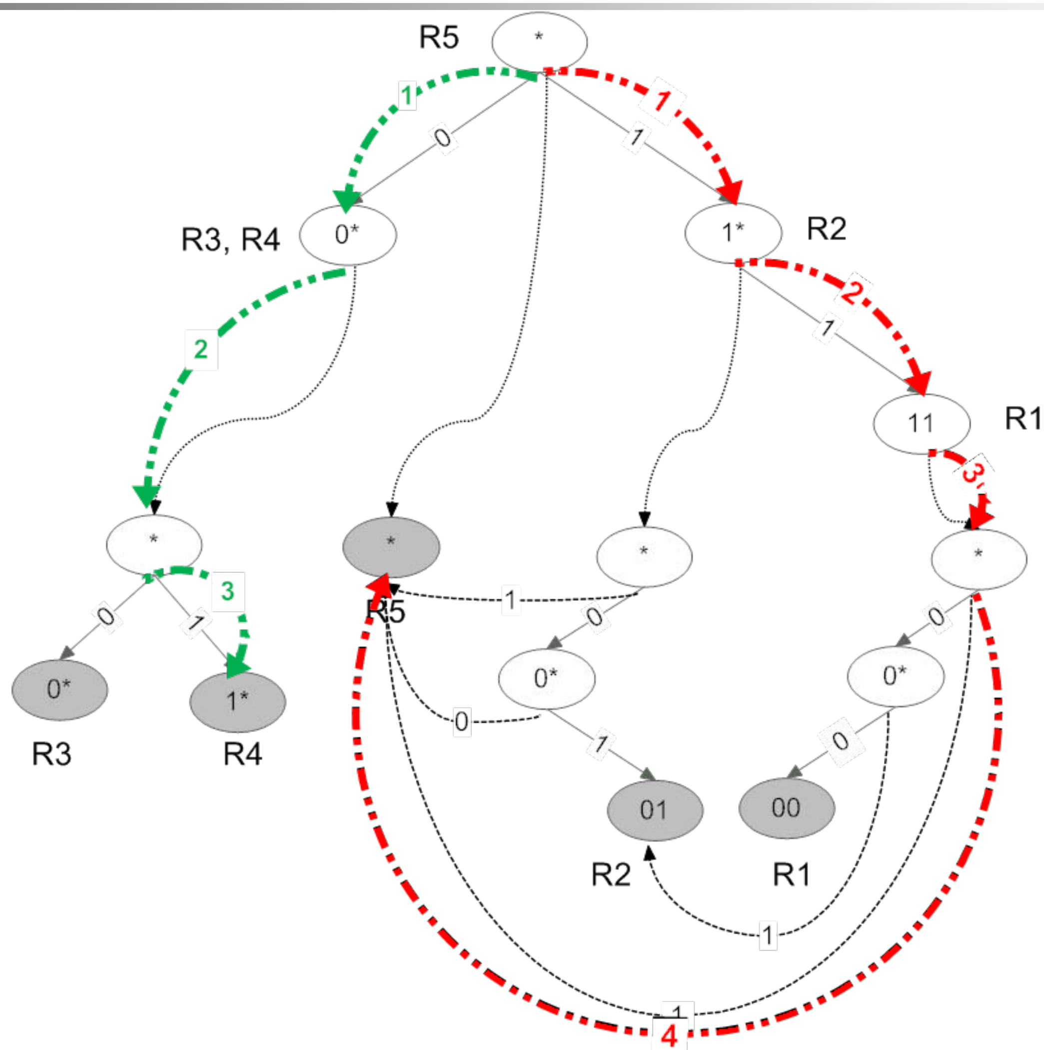




- No back-tracking search: O(dW) time
- Rules may appear multiple times: O(Nd) space

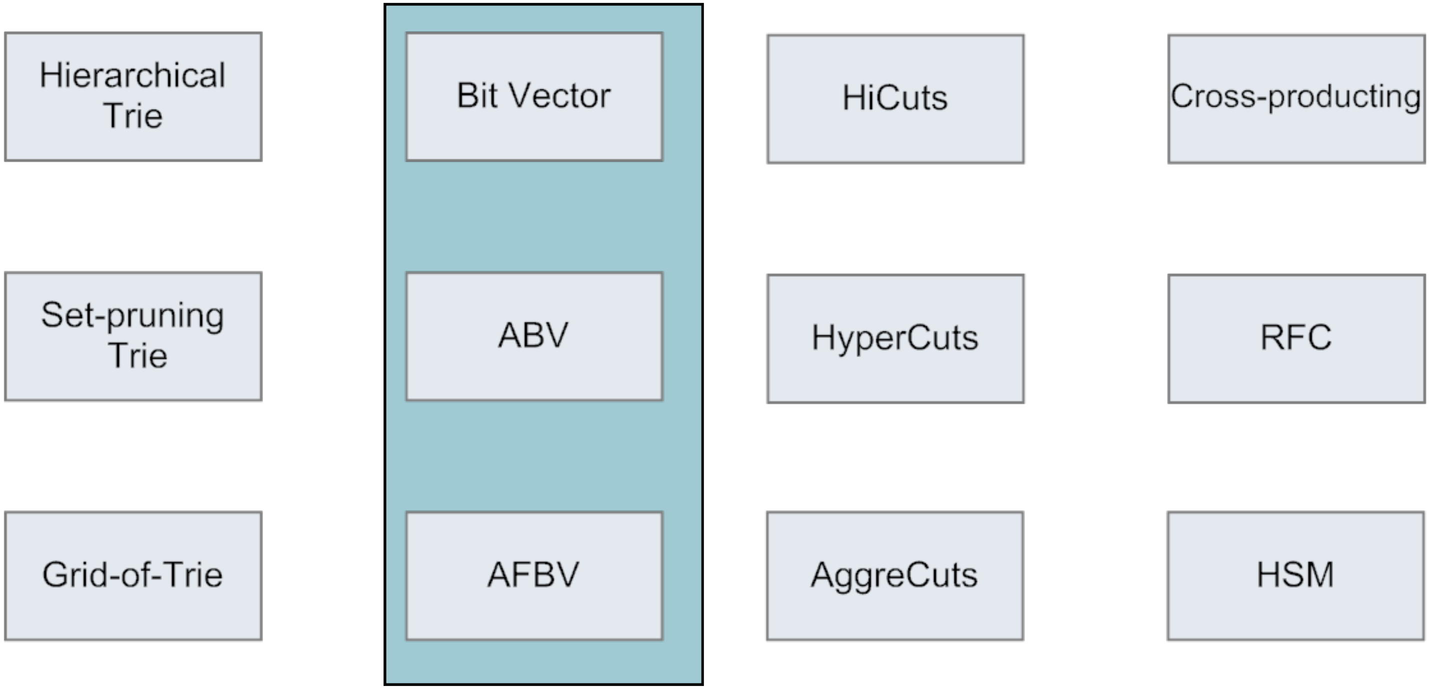
Grid of Tries



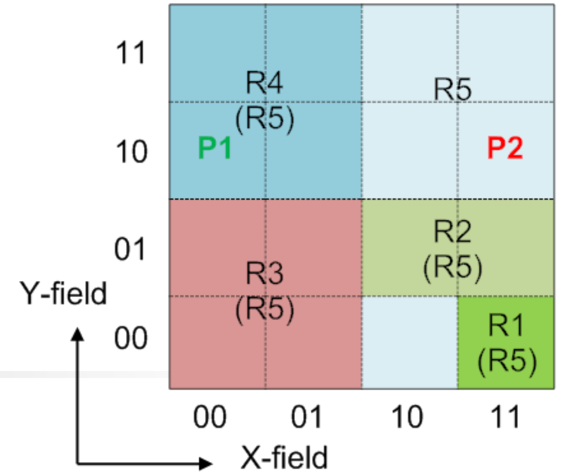


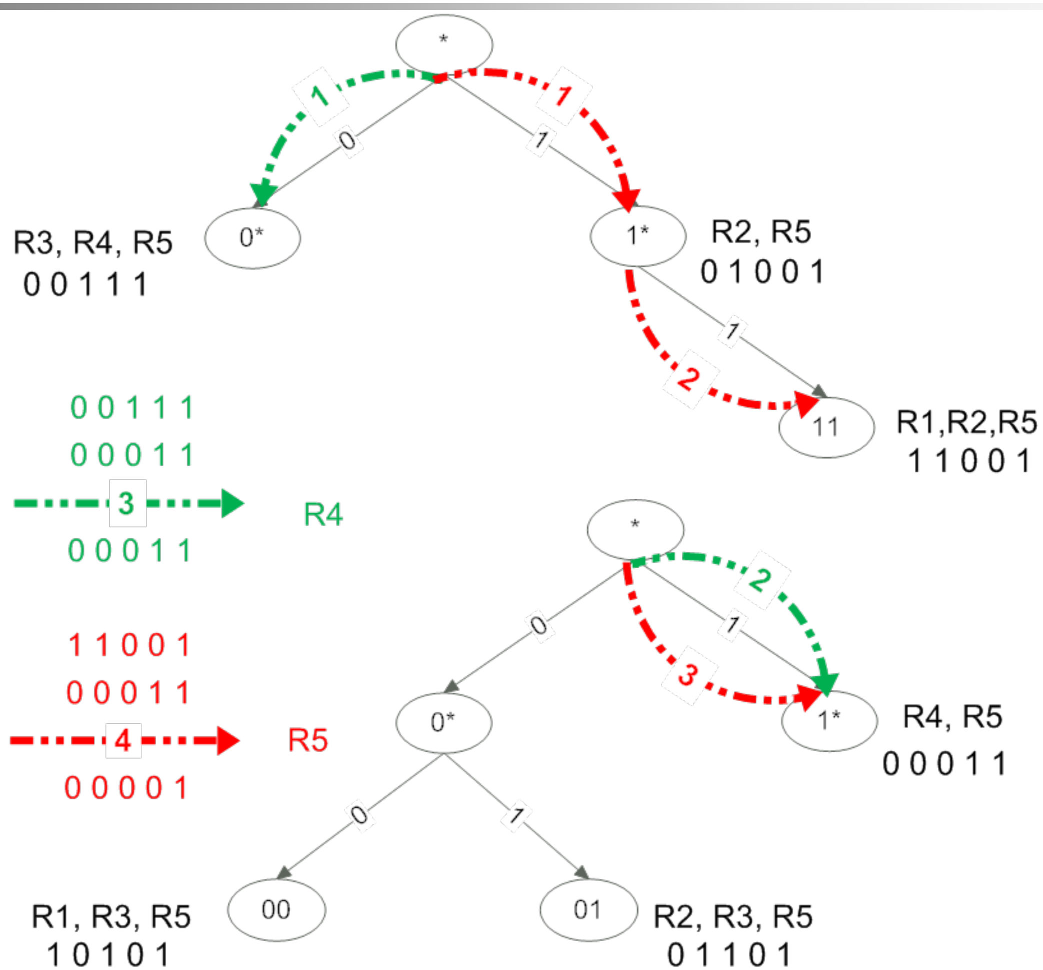
- No back-tracking search: $O(dW)$ time
- Rules appear only once: $O(N)$ space
- Only work for 2-D scheme

Packet Classification Algorithms



Bit Vector



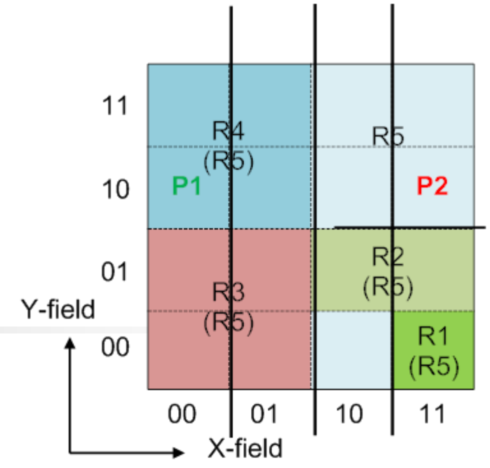


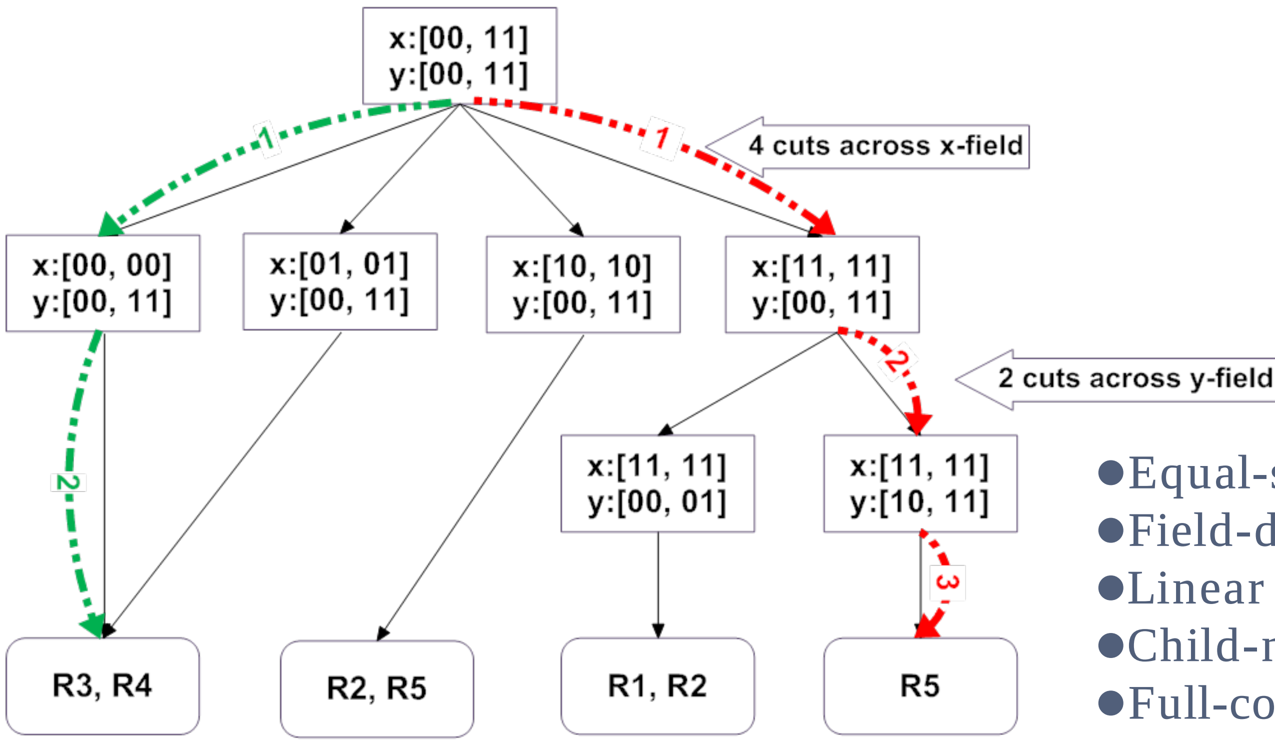
- Field-independent search: $O(dW+N)$ time
- Bitmap Storage: $O(dN^2)$ space
- Bitmap comparison is time-consuming

Packet Classification Algorithms

Hierarchical Trie	Bit Vector	HiCuts	Cross-producting
Set-pruning Trie	ABV	HyperCuts	RFC
Grid-of-Trie	AFBV	AggreCuts	HSM

HiCuts

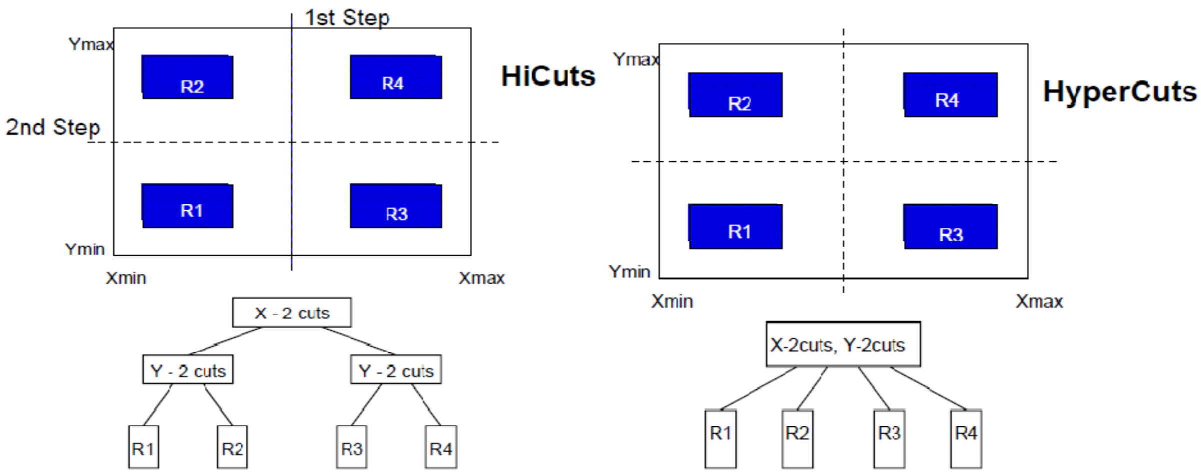




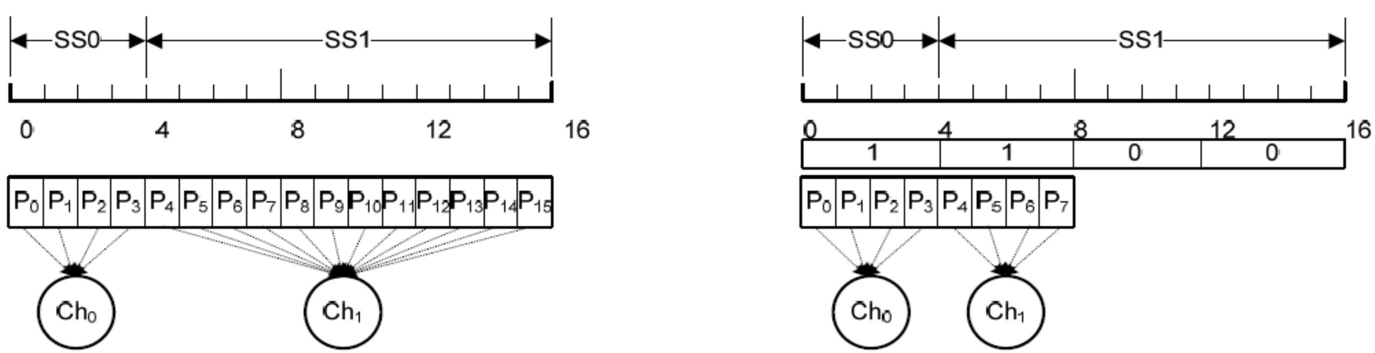
- Equal-sized space partition
- Field-dependent search
- Linear search at leaf-node
- Child-node merge
- Full-covered region check

HyperCuts and AggreCuts

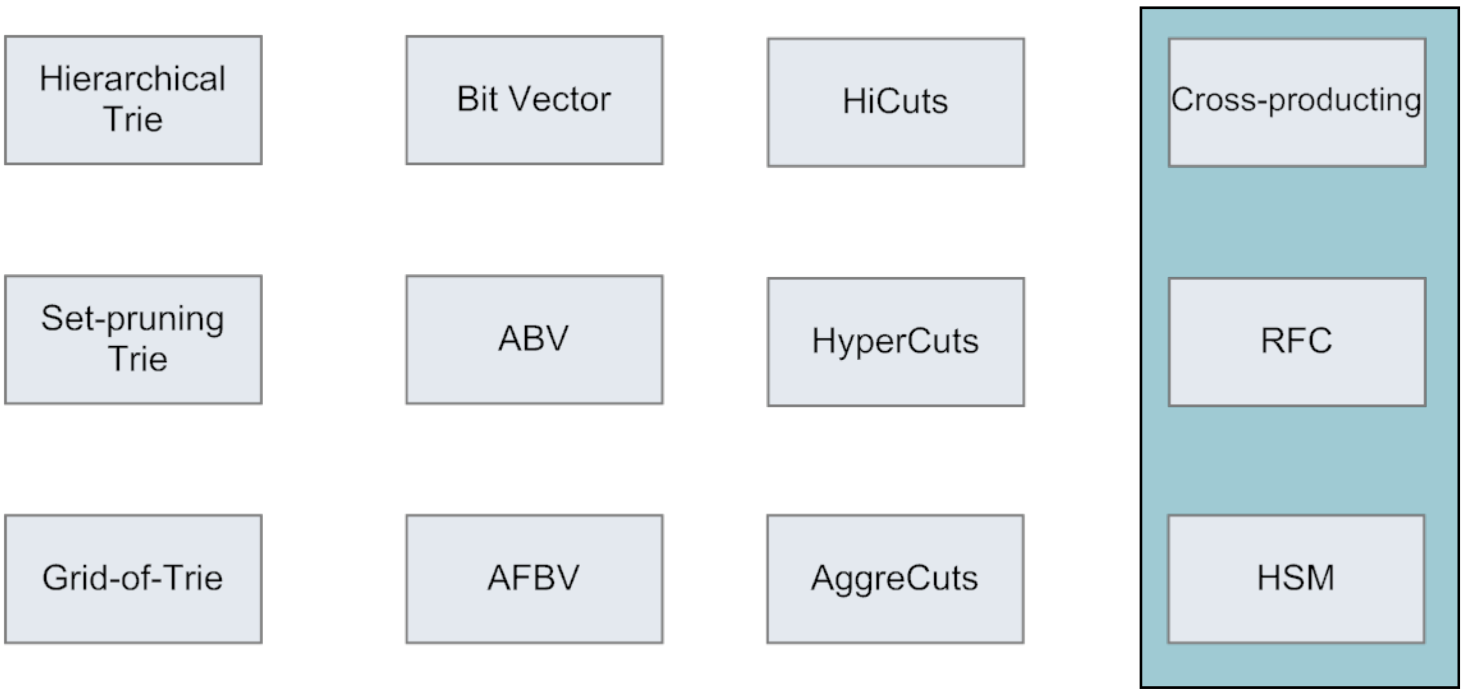
HyperCuts: multi-dimensional cuttings



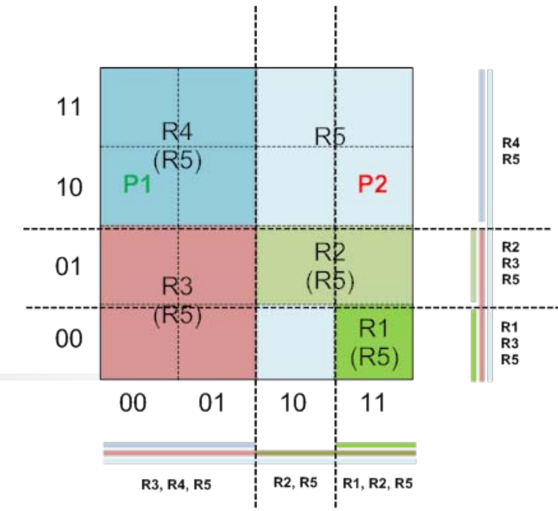
AggreCuts: pointer array compression

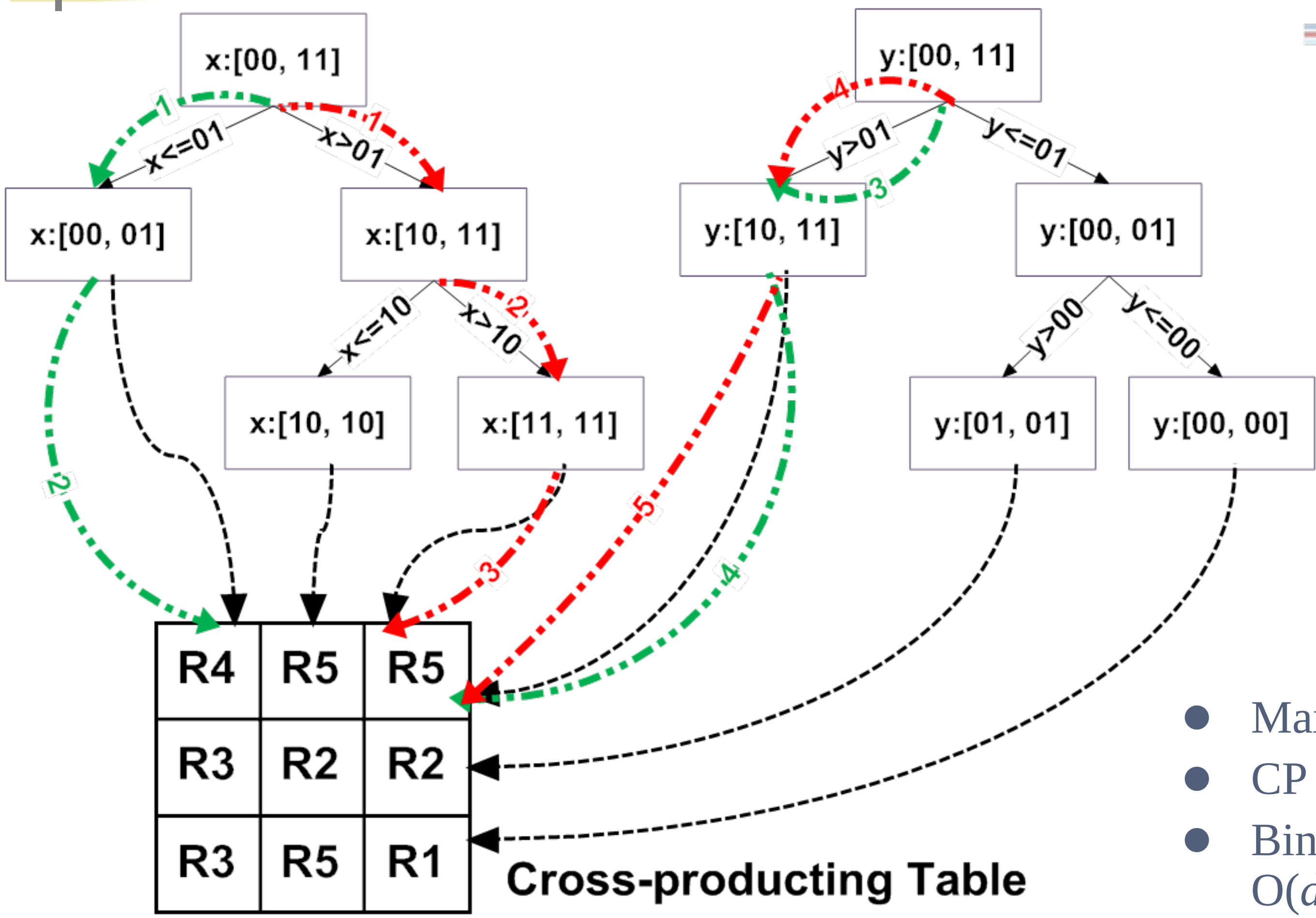


Packet Classification Algorithms



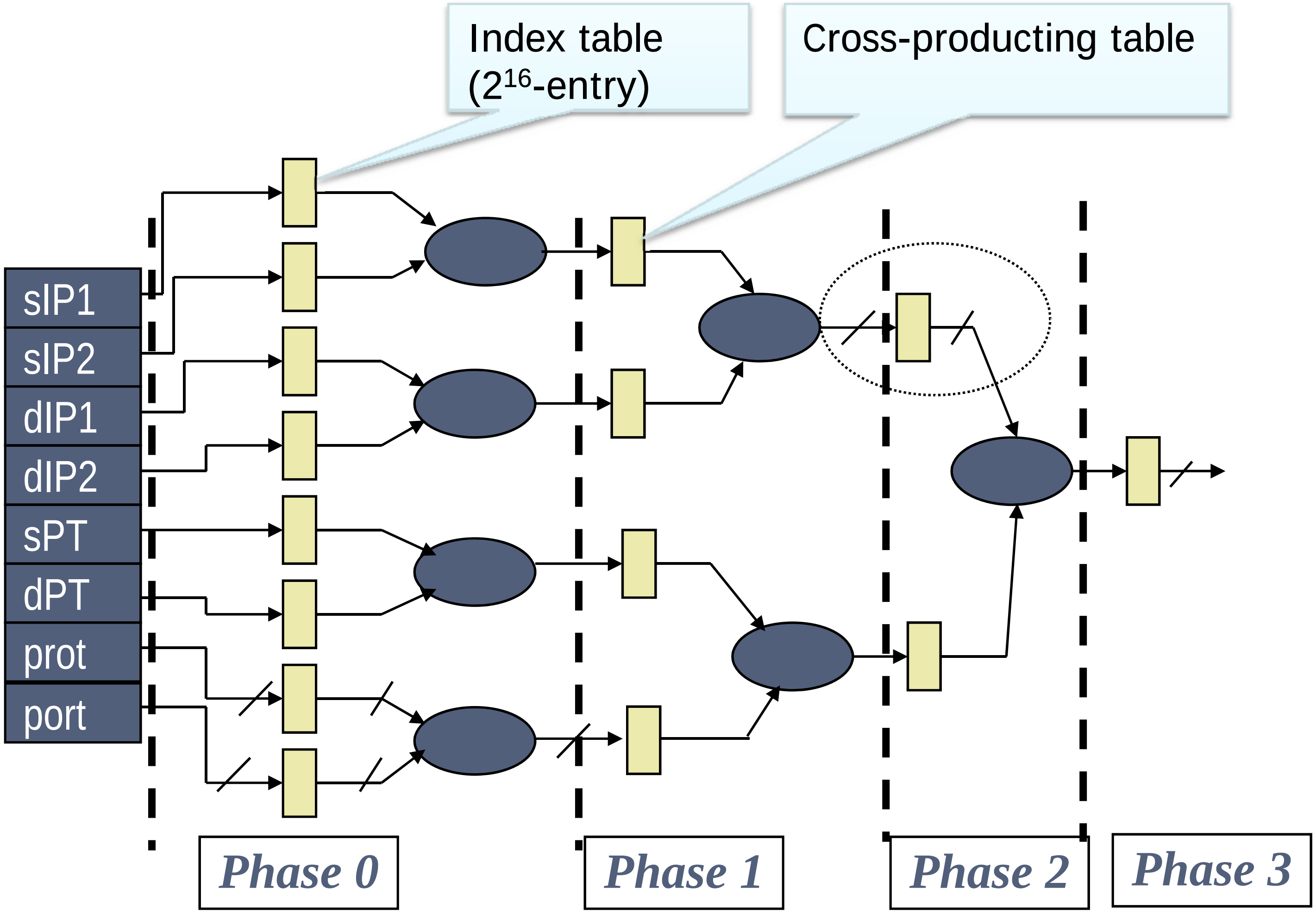
Cross-producting





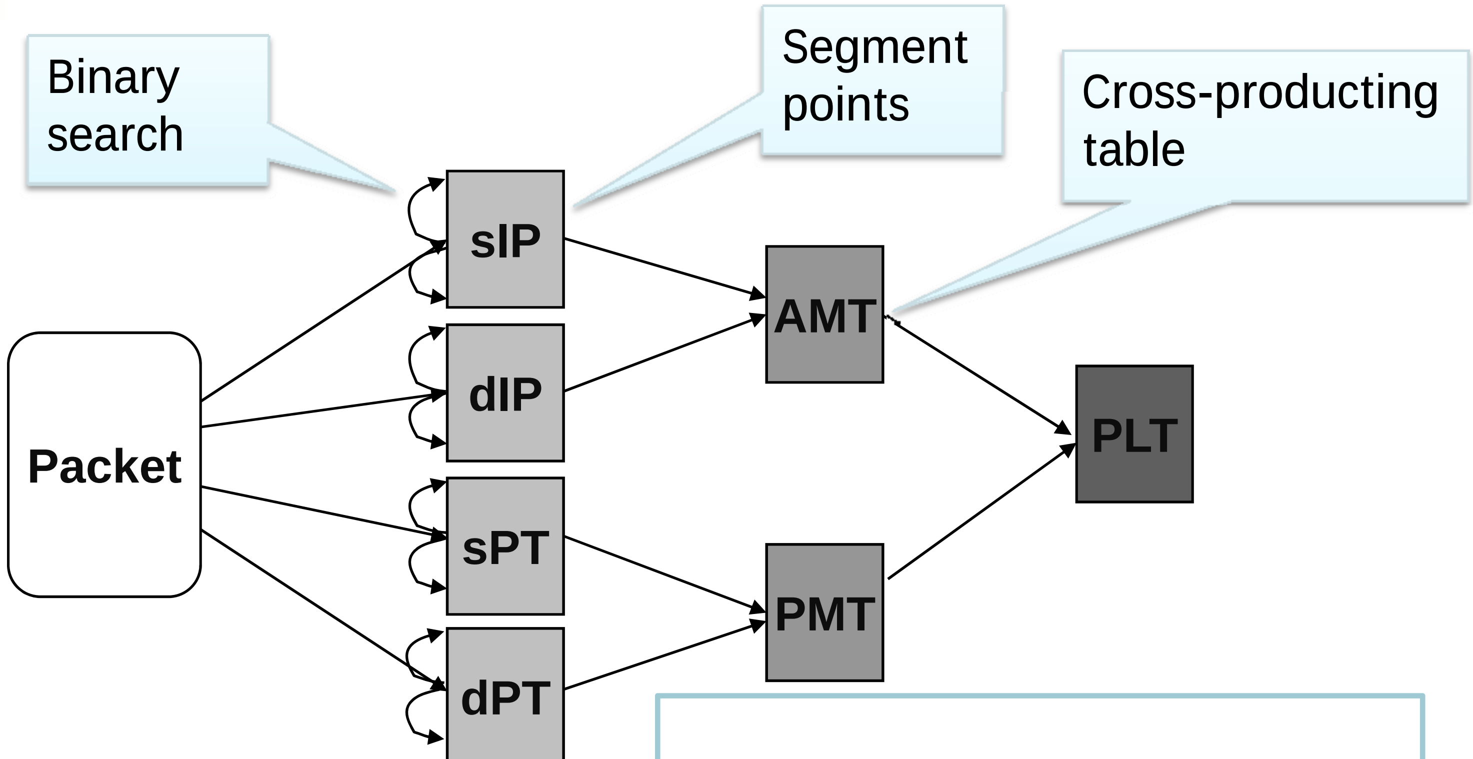
- Max#segments: $2N+1$
- CP table size: $O(N^d)$
- Binary search: $O(d*\log(N))$

RFC



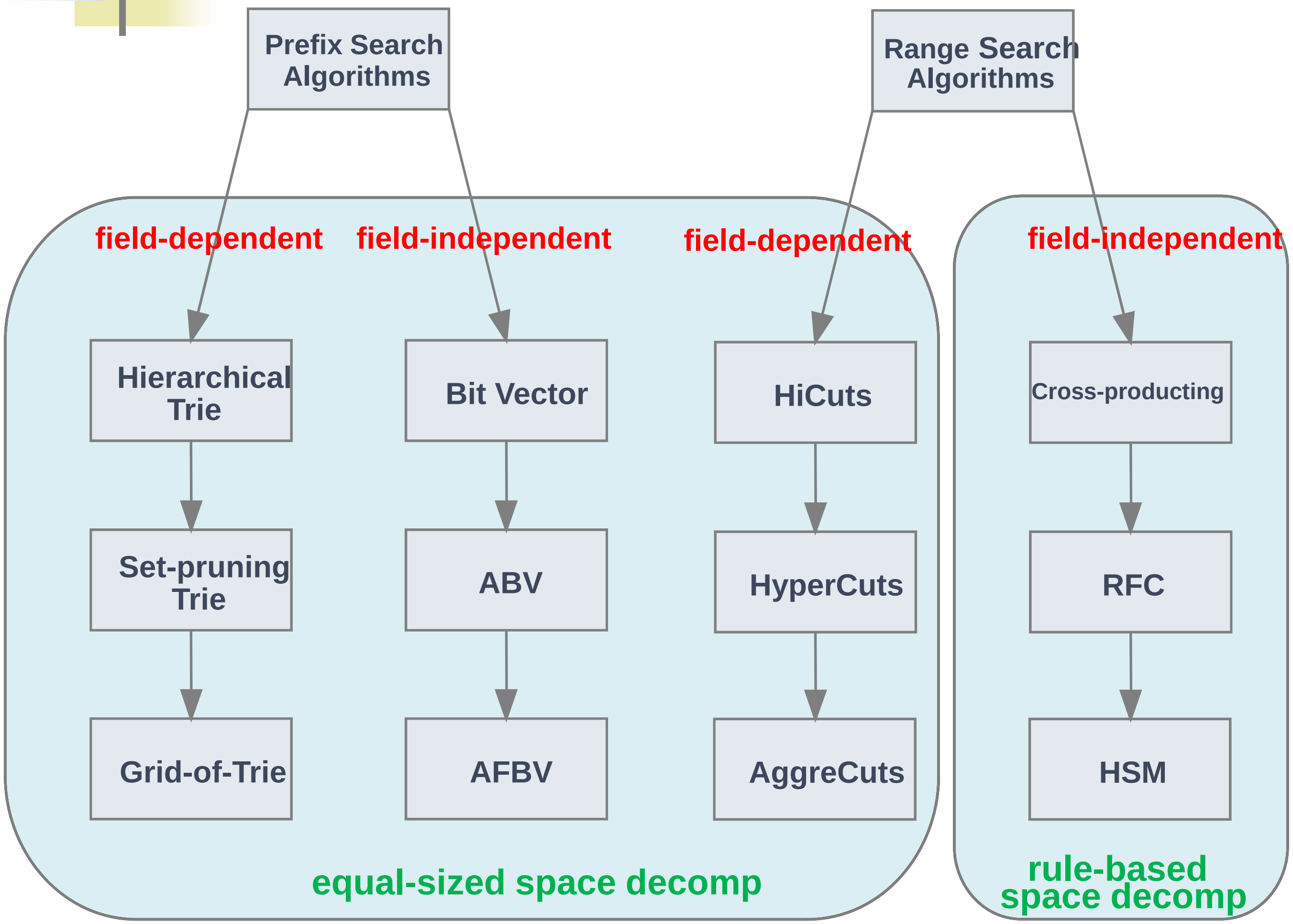
Index table
(2^{16}-entry)
Cross-producting table
sIP1
sIP2
dIP1
dIP2
sPT
dPT
prot
port
Phase 0
Phase 1
Phase 2
Phase 3

HSM



AMT: Address Mapping Table
PMT: Port Mapping Table
PLT: Policy Lookup Table

Summary: Taxonomy



Decomp \ Recur	rule-based	equal-sized
field-independent	✓ HSM	✓ BV
field-dependent	?	✓ HiCuts

Our recent advancement

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HyperSplit: Motivation

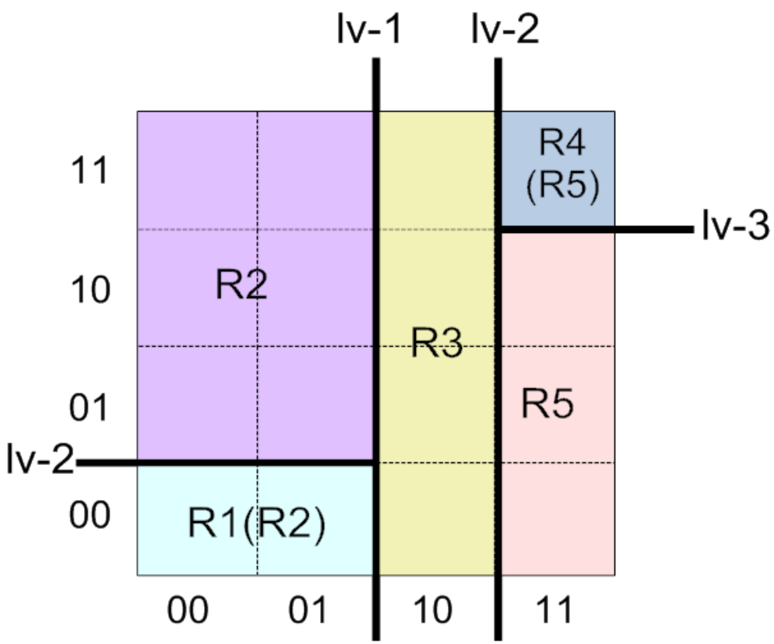
- High-speed classification
  - Speed is the most important performance metric
  - Speed should be bounded in the worst case
- Modest memory storage
  - Memory storage cannot exceed the overall system memory size
  - Modest memory storage enables the use of fast memory technology

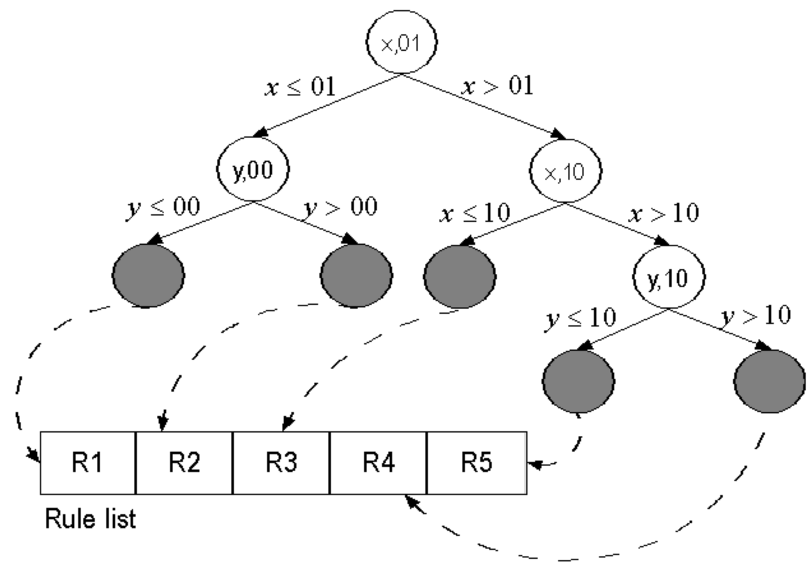
HyperSplit: Ideas

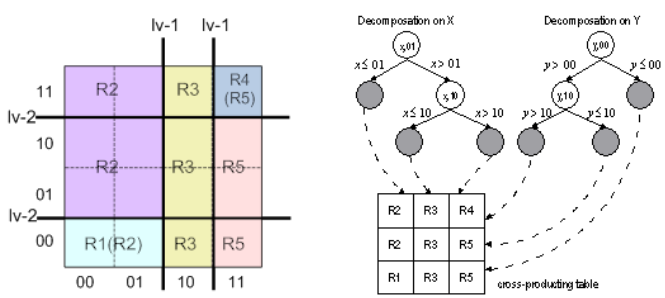
- Rule-based space decomposition
  - Binary splitting: **O (log(N))** search time
  - Intelligently select the splitting point
    - Heuristic-1: select the mid-value point
    - Heuristic-2: select the mid-segment point
    - Heuristic-3: select the weighted mid-segment point
- Field-dependent recursion scheme
  - Always select the most discriminative field to apply decomposition
    - For Heuristic-1 and Heuristic-2: select the field with the largest number of segments
    - For Heuristic-3: select the field with minimized average weight
  - Termination conditions
    - There're less than ***Thresh*** rules in current search space
    - The current search space is fully covered by all the current rules

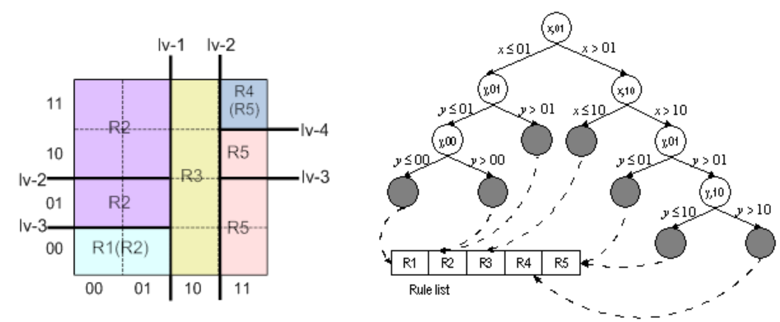
Data structure design and optimization also important, see paper.

HyperSplit: Example





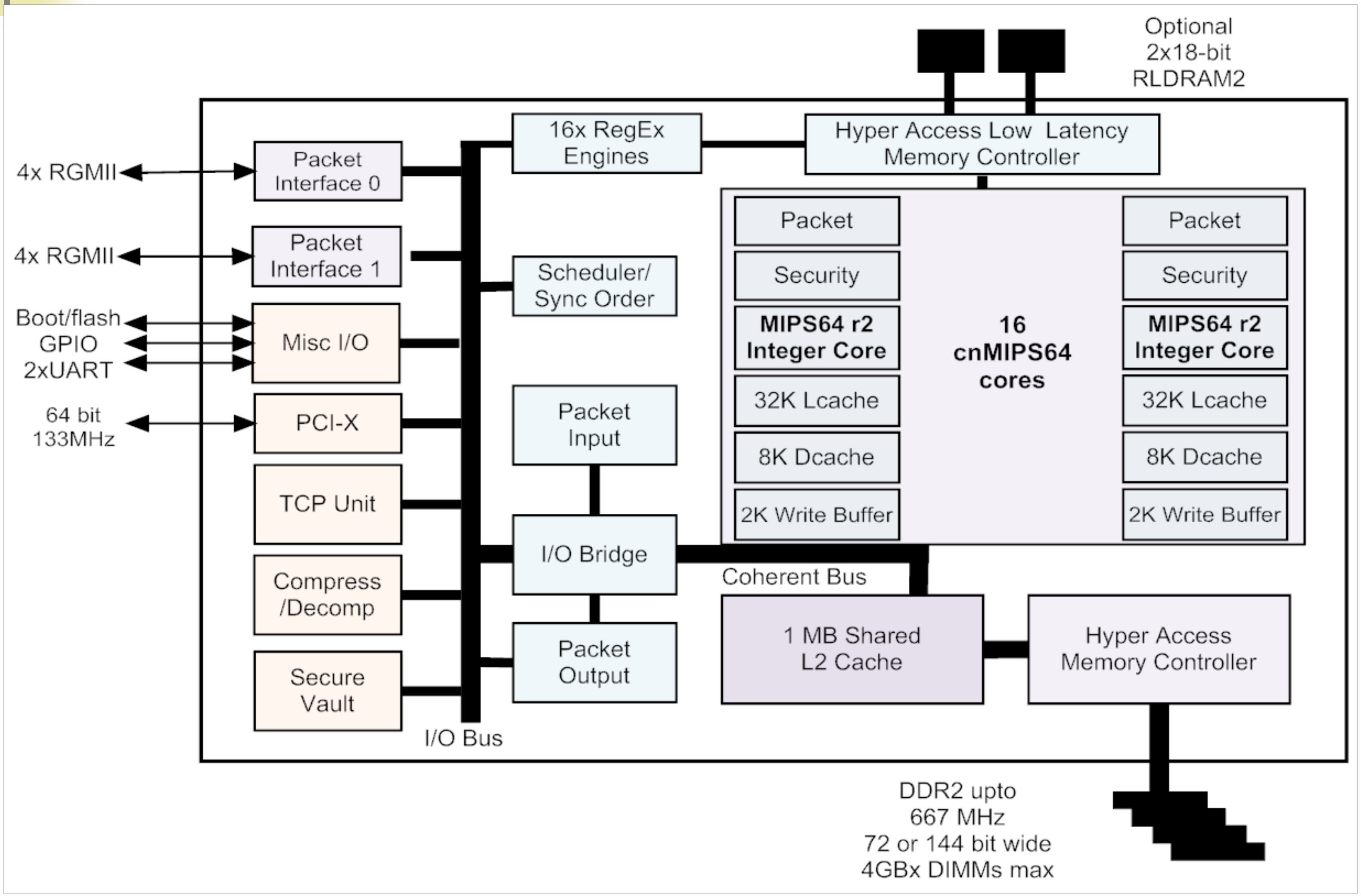




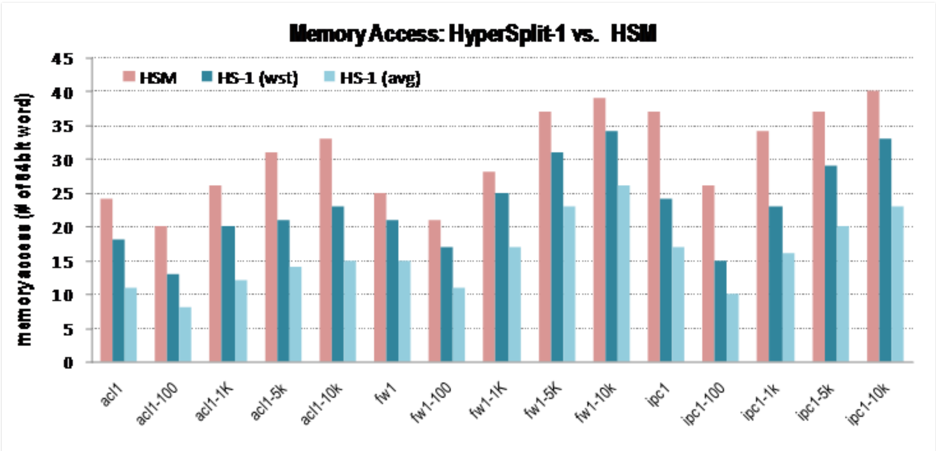
Data-set and Test-bed

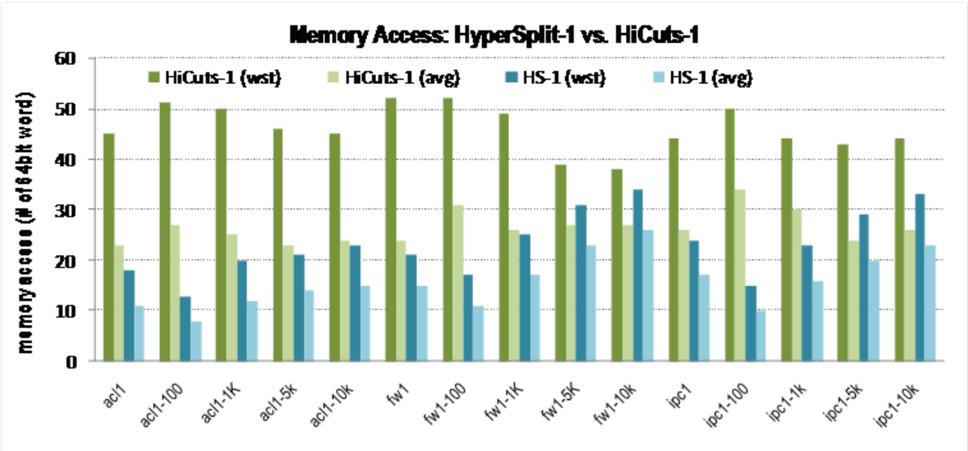
- Algorithms
  - HyperSplit-1, HyperSplit-8, HiCuts-1, HiCuts-8 and HSM
- Data-set
  - WUSTL Evaluation of Packet Classification Algorithms
    - 100~10K real-life 5-tuple firewall, ACL and IP Chain rules
    - http://www.arl.wustl.edu/~hs1/PClassEval.html
- Test-bed
  - Memory access, usage, and preprocessing time: 2.0GHz dual-core with 4GB DDRII memory runing Ubuntu 8.04LTS
  - Throughput: Cavium OCTEON 3860 multi-core processor runing in “Simple Executive” mode
  - SmartBit packet generator

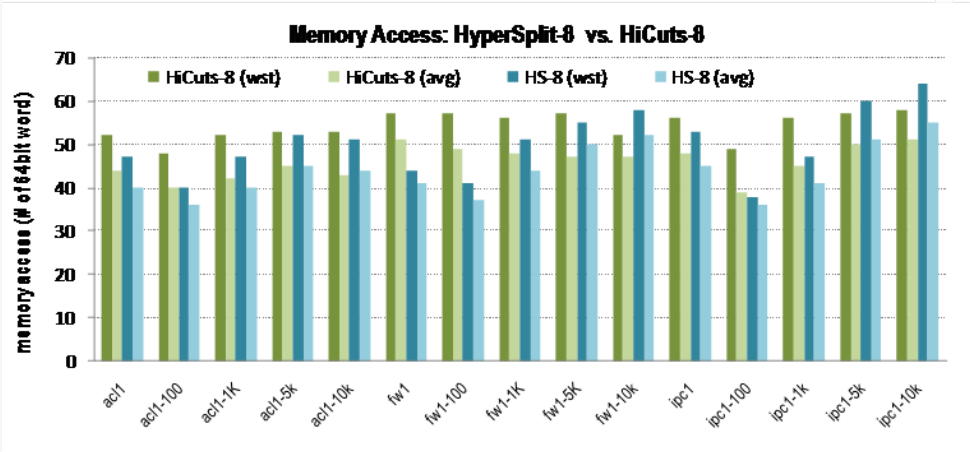
Cavium OCTEON 3860



Memory Access

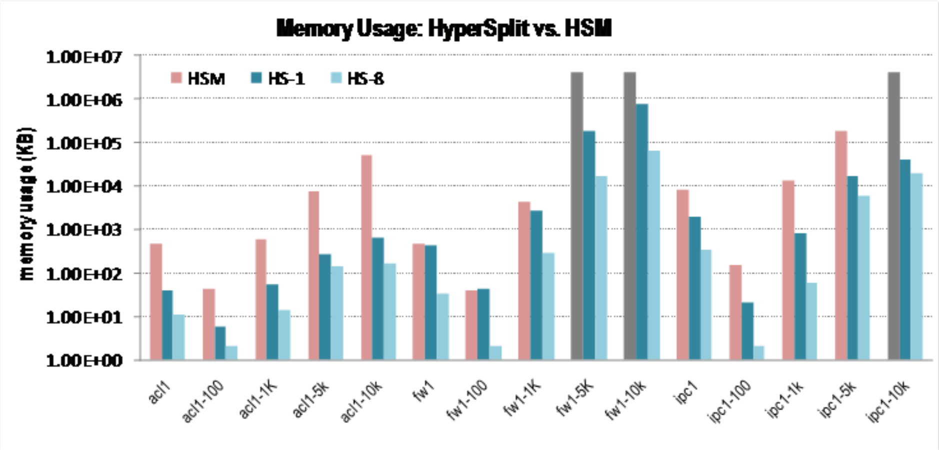


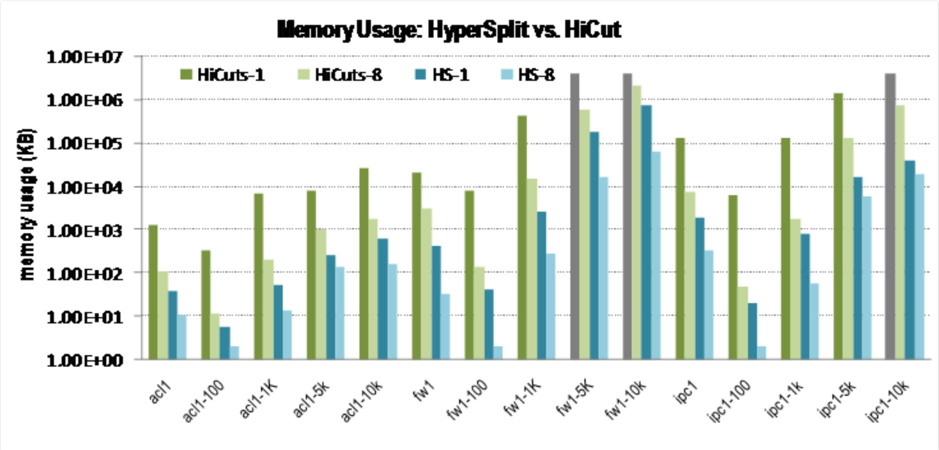




- HyperSplit-1 vs. HSM
  - 20~50% less access
- HyperSplit-1 vs. HiCuts-1
  - 50~80% less access
- HyperSplit-8 vs. HiCuts-8
  - 10~30% less access

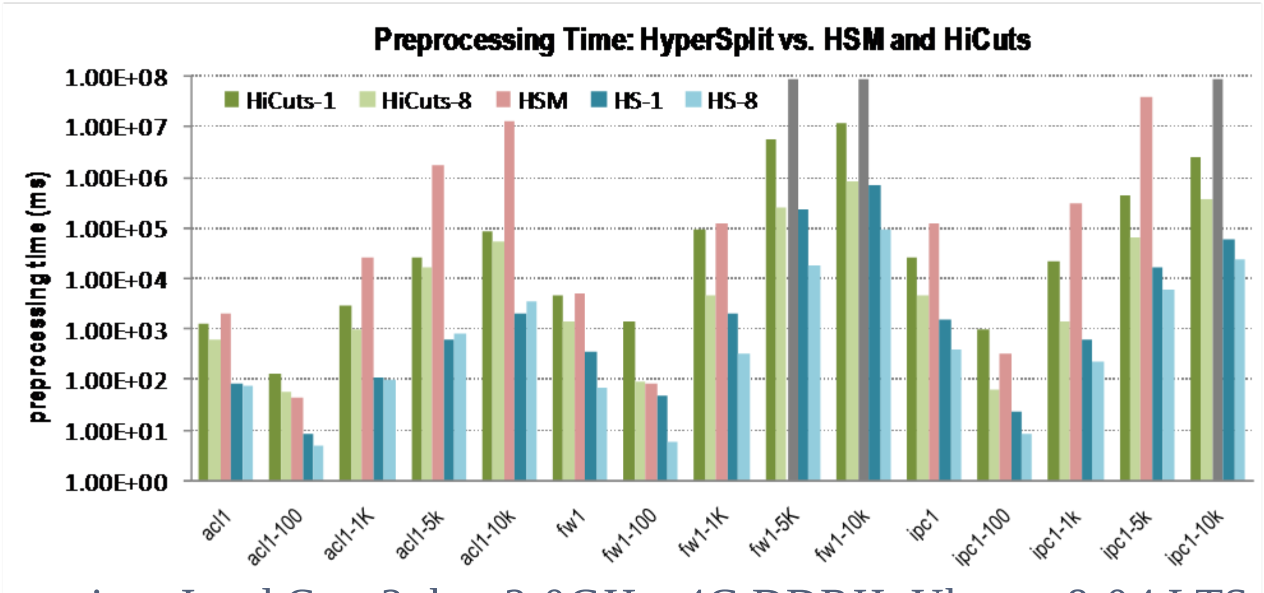
Memory Usage





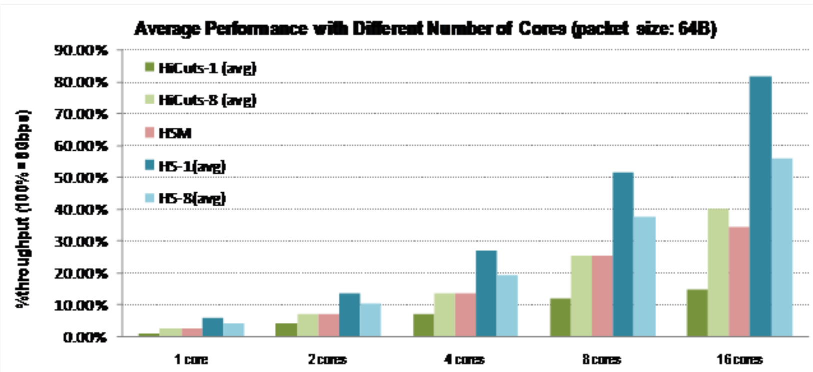
- HyperSplit-1 vs. HSM
  - 1~2 orders less memory;
  - HSM fails for fw1-5k, fw1-10k and ipc1-10k (due to 4GB+ memory usage)
- HyperSplit-1 vs. HiCuts-1
  - 1~2 orders less memory;
  - HiCuts-1 fails for fw1-5k, fw1-10k and ipc1-10k (due to 4GB+ memory usage)
- HyperSplit-8 vs. HiCuts-8
  - 1~2 orders less memory; successful for all rule-sets.

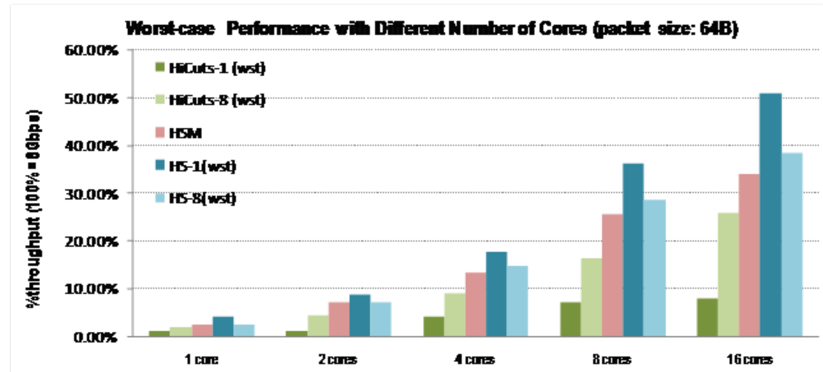
Preprocessing Time

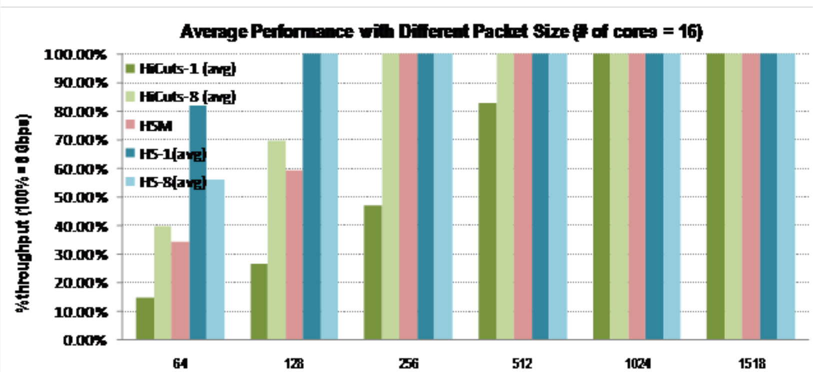


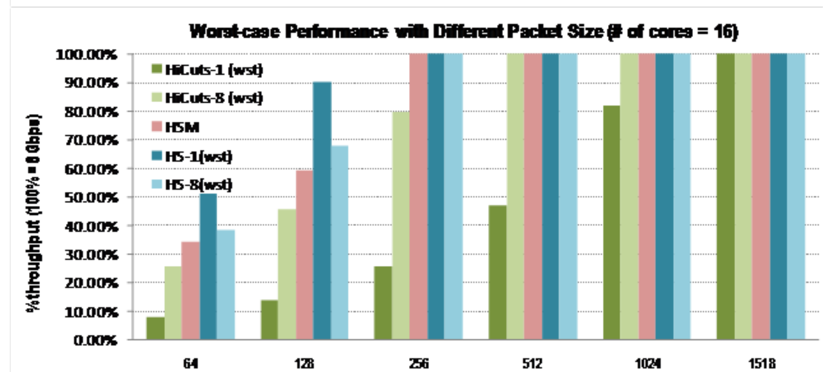
- Pre-processing: Intel Core2 duo 2.0GHz, 4G DDRII, Ubuntu8.04 LTS
- HyperSplit-1 vs. HSM
  - 1~4 orders less time
  - HSM fails for fw1-5k, fw1-10k and ipc1-10k (e.g. 24 hours for fw1-10k, and failed)
- HyperSplit-1 vs. HiCuts-1
  - 1~2 orders less time
  - HiCuts-1 fails for fw1-5k, fw1-10k and ipc1-10k (e.g. 4 hours for fw1-10k, and failed)
- HyperSplit-8 vs. HiCuts-8
  - About 1 order less time

Throughput









- 64B packet-size test with different # of cores:
  - HyperSplit: 6.4/4.2Gbps with 16 cores; HSM: 2.4Gbps; HiCuts: 1.1/3.2Gbps
- Variable packet-size test with 16 cores:
  - HyperSplit: 8Gbps with 128B+ packets; HSM: 256B+; HiCuts: 1024B+/256B+

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Conclusion and Discussion

- Conclusion
  - Theoretically: Explicit worst-case search time O(log$N$)
  - Practically: 6.4Gbps on OCTEON3860, apply to all data sets @WUSTL
- Discussion
  - Adaptive to different memory hierarchy rather than the L2-DRAM coherent memory system?
  - Policy-based switching rather than routing?
  - Application identification rather than flow classification?

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Thanks!
Questions?