Many Fields Packet Classification Using R-Tree and Field Concatenation Technique

1st Aladdin Abdulhassan  
Department of Computer Engineering, Kermanshah, Iran  
Razi University  
Kermanshah, Iran  
alaaabbas069@gmail.com

2nd Mahmood Ahmadi  
Department of Computer Engineering, Kermanshah, Iran  
Razi University  
Kermanshah, Iran  
m.ahmadi@razi.ac.ir

Abstract—Software Defined Networking is an approach which decouples the software based control plane from the hardware based data plane proposed for enterprise networks; OpenFlow is the most famous flexible protocol that can manage network traffic between the control and the data plane. Software Defined Networking (SDN) requires up to 18 fields of the packets header to be checked against a big many-fields ruleset to categorize packets into flows, the process of categorizing packets into flows is called packet classification. Network switches process all packets belonging to the same flow in a similar manner by applying the same actions that defined in the corresponding rule. Packet classification facilitates supporting a new services such as filtering, blocking unsafe sites traffic, routing packets based on the packet’s header information, and giving priority to specific flows. High performance algorithms for many-field packet classification had been gained much interest in the research communities. This paper presents a new method to implement the many-fields packet classification of SDN flow table using Rectangle Tree (R-Tree). In this method, source and destination IP addresses from each flow table entry have been converted to a two dimensional point. The remainder of rule’s fields have been concatenated into a single field by taking the most important bits with rules’ ID in order to be inserted into the R-tree, for each rule an effective small binary flag used to indicate the field’s size, type and ranges. Subsequently, searching is performed on rectangle tree to find the matched rules according to the highest priority. In the simulation using the class-bench databases, the results show that this method achieves very good performance, classification speed and reduces the number of memory accesses significantly.

Index Terms—Software Defined Networking; OpenFlow; Packet Classification; R-Tree.

I. INTRODUCTION

Software-Defined Networks (SDNs) have gained a growing attention in recent years. In SDNs, the packet processing functionality is managed by a logically centralized controller, that makes it easier for programmers to control the network behaviors directly by configuring the forwarding rules installed on each distributed switch [25]. For scalability and fault tolerance in some case the controller is often replicated and distributed [4], [9].

The real needs for SDNs technologies have been driven by specific network requirements such as advent of Cloud services, the mobile devices explosion, and server virtualization within the large data center networks. Outside the data center, however, SDNs could provide open APIs and network flexibility to support a dynamic traffic flows that can reduce latency and guarantee Quality of Service for networks such as WANs and campus networks.

The most famous protocol that can manage SDNs network traffic called OpenFlow, which facilitates the creation and introducing a new network protocols and policies by providing an abstraction of network devices and operations [25]. These protocols are proceed via the network controller. The network controller works as a compiler that can take abstract policies provided by network designers and generate a specific rules in the table for each network switch [15].

One of the main issues for network community in recent years is the packet classification, it is the ability to classify the incoming packets to specific flows. The packet classification is needed for modern routers to provide different qualities of service to various applications. OpenFlow-based software defined networking switches can support a new services such as filtering, blocking unsafe sites traffic, routing packets based on the packet’s information, and giving priority to specific flows. Thus, packet classification is used in modern network applications such as accounting, filtering, monitoring, security, etc. [13].

Packet classification is based on rules which define multiple fields of packet headers, the value of each field can be an exact, a range, or a prefix value. All investigated fields of an incoming packet are compared with the rules. Each rule is associated with an action to process an incoming packet if matches a rule, that means each field of the rule matches the corresponding field of the incoming packet. In fact, one of two matching types may be required, first type is single match packet classification, that type is required for services such as firewalls and quality of service that require the capability to isolate and distinguish traffic in different flows for suitable processing, this type of packet classification yields the best matching rule (the rule with the highest priority)[27]. The second type is the multi-match packet classification. This type is required for a services that produce all matching rules such as traffic accounting and intrusion detection [18], [5]. It can also be used by multifunction devices that perform single match packet classification for each function [7], [33], [34]. The matching process in packet classification requires more than 15 fields per flow to be compared with thousands of
rules in a ruleset. Hence, it is a great challenge to design a convenient packet classification approach that can consider the growing number of fields and rules in ruleset, and new fields updating capability.

OpenFlow Switches required a high throughput, latency and update cost, this requirements become harder with the growing complexity of a ruleset. Hence, packet classification remains challenging problem for next development generation. Current solutions [1], [24], [17], [19], [29] generate good system performance for traditional 5-tuple packet classification problems, but they do not solve the many-field packet classification problems that can deal with the growing fields counts and rulesets size, a longer processing latency and bigger space requirement. Even the many-field packet classifications with 5-tuple TCAM solutions required high implementation cost because of the big rulesets size and arbitrary field types.

In our proposed method the popular R-tree is used to present the many-field packet classification solution. The IP source and destination addresses(SA, DA) prefixes are converted to a two-dimensional data to be inserted into R-tree, the remainders of rules fields are concatenated into a string and inserted into leaves nodes where the real data of R-tree is. A small flag is used to indicate the wild-card and range fields (source and destination ports numbers). In the querying phase, all overlapping rectangles are retrieved as search results, based on the previously stored information about rules priority of each rectangle, the rectangle containing highest priority is selected as matching result. Using R-tree, more than one rule is indexed in each rectangle; therefore, it decreases the height of the tree and memory accesses, in the result, our proposed method shows a very good throughput for searching phase.

The main contribution of this paper is as follows:

• Organizing rulesets as a rectangular tree data structure by proposing a new algorithm based on R-tree algorithm and using the most effective ruleset’s fields as a key to construct that tree.
• Proposal of a new extendible and easy implementation method to append the ruleset fields (static length and range fields) in the R-tree so that it will be easy to extract these fields to use them in the query phase.
• Generating of varying 15 fields ruleset types and sizes and a tracing data.

The remainder of this work is organized as follows. Section 2 gives background about related works on many-fields packet classification problem and discusses the motivation of this paper. Section 3 presents a background about the R-tree. Section 4 presents and describes the proposed packet classification algorithm. In Section 5, we discuss about the simulation results. Section 6, concludes the paper.

A. Related Works

Several research groups observed many-field packet classification challenges and tried to come up with different solutions. Some groups tried to introduce new solutions such as tagging approach [8] that classifies packets at the edge switch and inserts tags into packets for a fast packet forwarding in a network, hashing approach [22] classifies the first packet in a flow and uses hash table lookups for the following packets to improve the performance of packet forwarding, decomposition-based approach [28] uses bit vector with hash tables, decision-tree-based approach [14] uses 2-d pipeline architecture with tree-to-pipeline mapping scheme, and hybrid-based approach [11] uses effective bits with look-up tables to lower the computation cost and improve the system performance [12].

Other research groups focus on avoid the previous many-field packet classification algorithms weaknesses, some solutions avoid the repeated packet classifications on the same packet at different network nodes and free extra processing capacity [12]. All proposed methods have been widely studied to improve their time complexity and memory requirements. The researchers try to optimize both time and storage complexities as much as possible. In general, the existing packet classification solutions can be classified to four groups[23], [6]. The first group is basic data structure group, contain the simplest solution for packet classification such as Linear Search, Hierarchical Tries, and Hierarchical Binary Search Tree (HBST) [31], [20], usually this group require small amount of memory but it does not scale well for large rulesets. The hierarchical tries [31] is a binary trie extension, it constructs a one dimensional trie for each prefix, it’s drawback is it needs an expensive backtracking search time. The second group is the geometry based methods group, this group contain the solutions that use trees to solve the many-field packet classification problem such as Splay Tree based Packet Classification (ST-PC), and Area-based Quad Trie (AQT) [32], [3]. AQT is a 2-dimensional search trie that build a two-dimensional quad-trie by build a one-dimensional binary trie to source and destination prefixes at the same time. Each node in quad trie has four children, the quad trie has its weaknesses because it has much empty internal nodes and its so difficult to update the multiple one-dimensional tables. The third group is the heuristic methods group, the HyperCuts [26] is the most well known heuristic method, it uses a preprocessing to the filters set to great a decision tree which contain a small number of filter in its leaves, after that it uses a cutting techniques to eliminate the irrelevant rules. The preprocessing classifiers require much time and that effect the search time in HiCuts. The fourth group is the hardware based schemes group, this group contain hardware solutions such as Ternary CAM, and Bitmap Intersection [26]. Hardware solutions usually have high performance but they experience a poor scalability and portability [23].

In our proposed solution we use the R-tree which avoids the most essential problem of the trie structures by reducing the large number of empty nodes which is not associated with rules.

II. R-TREE

The R-tree dynamic index structure for spatial data proposed by Guttman in 1984 [10]; Spatial data is information about a physical object normally arise in numerous applications such
as computer-aided design, computer vision, geographical information systems and robotics. This information can be represented in a geographic coordinate system as numerical values. R-trees used to dynamically organize a set of d-dimensional geometric objects, these objects are represented as minimum bounding d-dimensional rectangles (MBRs). Each MBR represented as node in R-tree and contain a pointers to its children except the leaves node which contain a pointers to the database objects. The R-tree represents a very useful filtering technique to minimize the costly direct inspection of geometric objects.

The original R-tree of order \((m, M)\) has the following features:

- Each leaf node (except if it is the root) can contains up to \(M\) entries, the minimum possible number of entries equal \(m \geq M/2\). Every entry is of the form \((\text{mbr}, \text{oid})\), so that mbr stand for the minimum bounded d-dimensional rectangle that contains the object and oid is the objects ID.
- Each internal node can store between \((m \geq M/2\) and \(M\)) entries of form \((\text{mbr}, p)\), where \(p\) represent a pointer to a child of the node, and \(mbr\) is the MBR that contains the MBRs stored in this child.
- Root node can store 2 entries as minimum, unless it is a leaf (can store zero or a single entry).
- R-tree is a height-balanced tree (all leaves at the same level).

As mentioned above the R-tree is a height-balanced tree, from many dimensions R-tree involve a generalization of the B+-tree structure [16]. R-trees are dynamic data structures, i.e., to handle R-tree insertions or deletions operations, the global reorganization is not necessary. Fig.1(a) shows a MBRs set of some geometric data. These MBRs are R4-R14, these MBRs are stored at the leaf of the R-tree. The same figure demonstrates the three MBRs (R1, R2, and R3) that organize the above mentioned rectangles into an internal node of the R-tree. Assuming that \(M = 4\) and \(m = 2\), Fig.2 depicts the corresponding R-tree. It is explicit to mention here that different R-trees can represent the same data rectanges set because of the resulting R-tree is highly depend on the the insertion (and/or deletion) order of its entries. Assume that an R-tree stores \(N\) data rectangles then the maximum value for its height \(h\) is:

\[
h_{\text{max}} = \log_m N - 1
\]

And by summing the maximum possible number of nodes per level, the maximum allowed number of nodes in such R-tree is equal to:

\[
h_{\text{max}} = \sum_{i=1}^{\log_m N} \frac{N}{m^i} = \frac{N}{m} + \frac{N}{m^2} + \ldots + 1
\]

A. R-Tree variants

The R-tree variants have the same structure and differ from each other only in considering different minimization criteria that affect on insertion, deletion operations, and how they perform splits during an insertion.

One of the most R-tree popular variants is R+-trees [30], objects in R+-tree may be divided into two or more MBRs and stored in different nodes to prevent overlapping of MBRs at same level, that directly effect the point queries so that visiting multiple paths is avoided. The second most popular variant of R-tree is R*-tree. In this variant, the overlapping between MBRs at the same level has been minimized, and the memory utilization has been maximized by using the concept of forced reinsertion and advanced node split technique [2]. The R*-tree differs from the classical R-tree only in the insertion algorithm. However, deletion operation and search queries remain unchanged. Also there are many unpopular variants of R-tree (The Hilbert R-tree, Compact R-trees, Priority R-tree and Logarithmic Dynamization R-tree) each of these variants differs from the original R-tree in how it chooses the appropriate sub tree and how it perform splits during an insertion.

III. PROPOSED PACKET CLASSIFICATION ALGORITHM

New SDN applications that support non best-effort services need to examine up to 15 fields in large lookup tables to classify incoming packets into different flows as depicted in Table I [16].

For development of new advanced services like SDN and NFV (Network Function Virtualization), more packet header fields were required. However, that represents new challenges to many-fields packet classification problems in term of storage requirement and system throughput. To address the scalability problem, it is necessary to lower the computation complexity, and system performance of many-field packet classification problem need to be improved with the number of rules and fields in a ruleset. In this paper, the proposed many-field packet classification using R-tree algorithm has been implemented as a classification system with an off-line rule programming process to construct the R-tree. Most significant field’s bits are offline concluded and concatenated to generate a single field for each rule to lower computation complexity, then the offline R-tree has been build by inserting this MBRs one by one into R-tree to optimize the online lookup throughput. A small binary flag has been generated to store useful information about exact field’s size, type and range for each rule, these flags are also concatenated at the end of created fields for corresponding rules as two or three Byte. Fig. 2 depicts the proposed packet classification structure, this figure contains two main parts, first part is the off-line proposed R-tree construction part, in this part the ruleset rules have to convert to rectangular object form by using the effective fields, and the remainders fields have to be concatenated, and to insert it to newly off-line constructed R-tree. The second part is the on-line packet classification part. This part is where the incoming packets classified to appropriate rule by querying the previously off-line constructed R-tree.
### Fig. 1. An example of a MBRs set of some geometric data(a), and their corresponding R-tree(b)

**TABLE I**

An example of OpenFlow packet classification ruleset (4 rules, 15 fields).

| Field Name | Field Length | Field Type | Rule 0 | Rule 1 | Rule 2 | Rule 3 |
|------------|--------------|------------|--------|--------|--------|--------|
| Priority   | 2            |            | 1      | 3      | 4      |        |
| Ingr       | 32           | E          | *      | *      |        |        |
| Meta-data  | 64           | E          |        | *      | *      | *      |
| Eth-src    | 48           | E          | 00:13:59:00:42:40 | 80:00:52:FC:07 | *      | 00:FF:FF:FF:FF |
| Eth-dst    | 48           | E          | 00:13:08:C6:54:06 | FF:FF:FF:FF:FF:FF | *      | 00:00:00:00:00:00 |
| Eth-typ    | 16           | E          | 0x0800 |        |        |        |
| VLAN-ID    | 12           | E          |        |        | 100    | 4095   |
| VLAN-priority | 3        | E          | 7      | 7      | *      |        |
| MPLS-lable | 20           | E          |        |        | 16000  |        |
| MPLS-tfc  | 3            | E          |        | *      |        |        |
| SA      | 32           | P          | 001*   | 00*    | 1*     | 1*     |
| DA      | 32           | P          | *      | 1011*  | 1011*  | 1*     |
| Prtl    | 8            | E          |        | TCP    | UDP    | *      |
| ToS     | 6            | E          |        |        |        | *      |
| SP      | 16           | R          | 0x5555 |        | 0x5555 | 2:2    |
| DP      | 16           | R          | 0x5555 | 123:123| 5:5    | 120:121|

### A. Off-line R-tree construction

Off-line R-tree construction stage shifts the computation cost of field traversals in many-field packet classification using the pre-computed data rulesets. It uses the most significant field’s (SA, DA) of a ruleset to generate MBRs which then used as a keys to build R-tree.

1) Minimum bounded rectangles(MBRs) creation: The value of each field in the ruleset can be a prefix, a range, or an exact value, the SA and DA prefixes were used to generate the MBR’s of the R-tree.

The first step in the R-tree construction is how to convert SA and DA prefixes into 2-dimensional data that can be inserted into the R-tree. IP SA prefix must be converted into 2 components $x_{\text{min}}$ and $x_{\text{max}}$. The minimum value of the prefix is used for the $x_{\text{min}}$ component and the maximum is used for $x_{\text{max}}$. The same steps are used to generate $y_{\text{min}}$ and $y_{\text{max}}$ from IP DA prefix, the value of $x_{\text{min}}$, $x_{\text{max}}$, $y_{\text{min}}$, and $y_{\text{max}}$ were represented as MBRs in R-tree.

Considering maximum length of prefixes (L), the IP prefix resulting MBRs are categorized into three different types:

- Dot: If the SA and DA lengths are exactly equal to L(maximum length) then the SA and DA ranges will be one value range and the corresponding MBR is assumed as a dot.
- Line: If the prefix length is less than L for SA or DA but not both, then one of these prefixes will be one value range and the other prefix will be more than one value range and the corresponding MBR is assumed as a line.
- Rectangle: If the prefix length is less than L for SA and DA prefixes then each of these prefixes will be more than one value range and the corresponding MBR is assumed as a rectangle.

Table II shows an example of how prefixes are converted into 2-dimensional data (L is set to 8). For instance, given rule R5 SA = 001*, and DA = 00100110, the first dimension x component bits are set to the 0-1 padded (shown as 001xxxxx). The x component value results in a range (32-64), the second dimension y component bits results in exact value (38). Therefore, the second discussed situation happens and the resulting type of data for R5 prefixes is a Line.

For each rule there is a flag to show the type and status of each field (wild-card, range and exact value) and there is a concatenated data field (CDF) that contains information collected from the rule fields (up to 15 fields). As explained
TABLE II

prefixes to 2-dimensional data converting and MBRs creation and categorization

|   | R4         | R5         | R6         | R7         | R8         | R9         | R10        |
|---|------------|------------|------------|------------|------------|------------|------------|
| SA Prefix | 110*       | 001*       | 10*        | 11011101   | 000*       | 0001*      | 001*       |
| DA Prefix | 0001*      | 00100110   | 11101*     | 00101111   | 10110110   | 11*        | 00111*     |
| X Bits   | 110xxxx    | 001xxxx    | 10xxxx     | 11011101   | 000xxxx    | 0001xxxx   | 001xxxx    |
| Y Bits   | 0001xxxx   | 00100110   | 11101xxxx  | 00110111   | 10110110   | 11xxxx     | 0011xxxx   |
| X Range  | 92-223     | 32-64      | 128-191    | 221-221    | 0-31       | 16-31      | 32-64      |
| Y Range  | 16-31      | 38-38      | 232-239    | 55-55      | 182-182    | 192-255    | 48-63      |
| Ingr     | 5          | *          | 1          | 4          | 3          | 1          |            |
| Meta-data| *          | 1          | 2          | 3          | 1          | *          | 1          |
| Eth-src  | 40         | FC         | *          | 00         | FF         | 30         | FA         |
| Eth-dst  | FF         | 07         | 00         | FF         | 0F         | 08         | 11         |
| Eth-type | 0x8100     | *          | 0x8100     | *          | 0x8100     |            |            |
| Vlan-ID  | 4095       | 100        | 4095       | 4095       | 2041       | 4095       | 100        |
| Prtl     | TCP        | *          | UDP        | *          | *          | TCP        | UDP        |
| ToS      | 0          | *          | 0          | 0          | 0          | 0          | *          |
| SP       | 69.69      | 80.80      | 53.53      | 5520:5520  | 1024:65535 | 0.65535    | 9003:9003  |
| DP       | 161:161    | 161:161    | 1433:1433  | 0.65535    | 120:121    | 53:35      | 0.65535    |
| Flag     | 010000     | 100001     | 101000     | 000001     | 000001     | 010000     | 000001     |
| DCP      | 000000     | 001000     | 011000     | 010001     | 010100     | 000001     | 001001     |
| Type of data | Rectangle | Line      | Rectangle | Dot        | Line       | Rectangle  | Rectangle  |

Fig. 2. Proposed packet classification structure.
in the Table II, the Fig.3 (a) shows how R5 constructs a straight line in the 2-dimensional area. After conversion of IP addresses, they are inserted into the rectangular-tree. These new data are inserted into leaf nodes, if there is room for new data they will be inserted into the relevant entries. Otherwise, the overflowed node will be split into two pieces and old data will be distributed between these new nodes. These changes will be propagated upward until the root node reached. The insertion algorithm of our proposed method follows the standard insertion method of R-tree.

Fig.3 (b) show simple prefixes of Table II form an R-tree. Three additional nodes were created containing 2 to 3 entries. The similar rules such as R4(110*, 0001*) and R7(11011101, 00110111) were located at the same node because of their similarity.

2) Remainders fields concatenation: The second step in proposed R-tree construction is the remainders fields concatenation. In this step the rest of rule fields (without SA, and DA prefixes) were concatenated to one long string by taking constant length of the most significant bits length from each field. For the range fields it is a challenge to be concatenated to other fields and be still usable fields. To solve this problem a binary flag is used to indicate fields type and even the fields state, some fields state in some rules is a wild-card fields(wildcard fields are not required for packet matching), the wild-card fields and range fields have been mentioned in the binary flag as "1", and the wild-card fields size has been set to "1" in the CDF, the source and destination port number fields are the only two fields in range form in the rulesets, when a source or destination port number(SP and DP) are the only range fields in rulesets, the range (0:65535) means wild-card for (SP and DP)fields, and its not required to take care for those field that are wild-card and rang at the same time in our binary flag because it is a range at the two cases. The binary flags are changed to character form and concatenated to the tale of the results fields.

3) R-Tree building and description: The last step in R-tree construction process is how to insert that 2-dimensional data into the R-tree. The algorithm for inserting a new data rectangle in an R-tree is presented in Algorithm 1.

To insert a new rule R, first we represent the new rule as rectangular data R.mbr, then append the concatenated fields (with port number range PNR and flag F) in R.c, R.p denotes the corresponding pointer to the next level, if the node is a leaf, then R.p denotes the corresponding object identifier (oid)(line 1-5). The tree will is traversed recursively from root node to appropriate leaf (line 6). At each level, all the rectangles in the current node examined and the rectangle that covers R.mbr with minimum area is selected (line 7, 8). and continue the search until the leaf reached. In case of selected leaf can accommodate R.mbr then R inserted to that leaf and update all nodes from that leaf to root node so that all of them cover R.mbr (line 9-13). In case of the selected leaf is already full,

R-tree construction.

Require: Type Rule R, Type Node RN  Insert a new rule R in an R-tree with root node RN
1: Let \(X_{\text{min}}= \text{R.SA-range minimum allowed value}\)
2: Let \(X_{\text{max}}= \text{R.SA-range maximum allowed value}\)
3: Let \(Y_{\text{min}}= \text{R.DA-range minimum allowed value}\)
4: Let \(Y_{\text{max}}= \text{R.DA-range maximum allowed value}\)
5: Let R.mbr denotes the corresponding MBR(\(X_{\text{min}}, X_{\text{max}}, Y_{\text{min}}, Y_{\text{max}}\))
6: Traverse the tree from root RN to the appropriate leaf.
7: At each level, select the node, L, whose MBR will require the minimum area enlargement to cover R.mbr.
8: In case of ties, select the node whose MBR has the minimum area
9: if the selected leaf L can accommodate R then
10: Insert E into L
11: for each rule in the path from root to L do
12: Call Update(MBRs) /*so that all of them cover R.mbr*/
13: end for
14: else
15: Let \(\epsilon\) be the set consisting of all Ls entries and the new entry R
16: Select as seeds two entries \(r_1, r_2 \in \epsilon\)
17: Form two nodes, \(L_1\) and \(L_2\), where the first contains \(r_1\) and the second \(r_2\)
18: Examine the remaining members of \(\epsilon\) one by one
19: assign them to \(L_1\) or \(L_2\)
20: if a tie occurs then
21: Assign the entry to the node whose MBR has the smaller area
22: end if
23: if a tie occurs again then
24: Assign the entry to the node that contains the smaller number of entries
25: end if
26: if during the assignment of entries, there remain \(\gamma\) entries to be assigned and the one node contains \(m - \gamma\) entries then
27: for each remaining entries to this node do
28: Assign to this node without considering the aforementioned criteria
29: end for
30: end if
31: for MBRs of nodes that are in the path from root to L do
32: Call Update(MBR) to cover \(L_1\) and accommodate \(L_2\)
33: Perform splits at the upper levels if necessary
34: if root has to be split then
35: Call create( a new root)
36: Increase the height of the tree by one
37: end if
38: end for
39: end if
then this leaf were split into two node (L1, L2) by selecting two seeds (r1, r2) from the set consisting of all Ls entries and the new entry R where the distance between r1 and r2 is the maximum among all other pairs of entries from ε(line 13-16), and puts them as initial entries into (L1, L2)(line 17), examine the remaining members of ε one by one to assign them to L1 or L2 depending on which of the MBRs of these nodes will require the minimum area to cover this entry. If a members of ε can be assigned to L1 and L2 at the same time, then it will be assigned to node whose MBR has the smaller area. If L1, L2 MBRs have the same area it will be assigned to node that contains the smaller number of entries (line 19-25). After that add these two new node(L1, L2) to the parent in the previous level, some time the previous level may overflowed too, and the overflows may propagate till the root node(line 31-33), when the root node also overflows, the root node has to split and a new root is created and height of the tree increased by one(line 34-37).

The above-mentioned insertion algorithm uses the simplest split algorithm called linear split algorithm which has linear time complexity. The linear split algorithm can minimize the probability of get both new created nodes (L1 and L2) as results for the same query. It tries to minimize the total area of the two new created nodes. The linear split algorithm chooses the most two divergent entries as seeds for the two nodes. Then it considers each remaining entry to one seed that can require the smallest enlargement. Consider the following insertion scenarios when we have the R-tree in Fig. 4 and we need to insert the new three nodes that have the following MBRs:

- MBR1(X=60-63, Y=31-64).
- MBR2=(X=280-290, Y=128-512).
- MBR3(X=10-12, Y=0-255).

In this R-tree of degree M=4, the red squares represent empty entries and black squares represents full entries, without considering Y ranges. To insert the first MBR, the insertion function will examine the root A and it will find that this MBR belongs to the first entry (X=0-255), then the search will descend to examine B and then H node. After examining H, the insertion function will find that H is a leaf node, so it represents the place where this MBR should be inserted. H contains 3 node entries so it can be inserted safely in H (maximum node entry is M=4) by creating new (X=60-63) entry and update the upper level entry to(X=32-63). To insert the second MBR, after examine the R-tree, it will take the path of (A-C-J); J is a leaf node, so it represents the place where this MBR should be inserted, but J is already full, the insertion function will call split function to create new two nodes L1, L2 and assigns first entry of node J (X=256-305) to L1 and last entry (X=280-319) to L2, then assigns each remaining entry (X=270-279, X=295-305, X=280-290) to the node requiring the smallest enlargement from L1, L2, that means L1 range will be (X=256-279), and L2 range will be (280-319), then assigns L1, L2 to the parent in the previous level which has enough place for them. To insert the last MBR, it will take the path (A-B-F), F is a leaf node, so it represents the right place where this MBR should insert, but F is already full, the split function will create new two nodes L1, L2 and assigns first entry of node F(X=0-2) to L1 and last entry (X=305-319) to L2, assign the remaining entries (X=270-279, X=295-305, X=280-290) to the node requiring the smallest enlargement from L1, L2, that means L1 range will be (X=256-279), and L2 range will be (280-319), then assigns L1, L2 to the parent in the previous level which has enough place for them. To insert the last MBR, it will take the path (A-B-F), F is a leaf node, so it represents the right place where this MBR should insert, but F is already full, the split function will create new two nodes L1, L2 and assigns first entry of node F(X=0-2) to L1 and last entry (X=305-319) to L2, assign the remaining entries (X=270-279, X=295-305, X=280-290) to the node requiring the smallest enlargement from L1, L2, that means L1 range will be (X=256-279), and L2 range will be (280-319), then assigns L1, L2 to the parent in the previous level which has enough place for them. To insert the last MBR, it will take the path (A-B-F), F is a leaf node, so it represents the right place where this MBR should insert, but F is already full, the split function will create new two nodes L1, L2 and assigns first entry of node F(X=0-2) to L1 and last entry (X=305-319) to L2, assign the remaining entries (X=270-279, X=295-305, X=280-290) to the node requiring the smallest enlargement from L1, L2, that means L1 range will be (X=256-279), and L2 range will be (280-319), then assigns L1, L2 to the parent in the previous level which has enough place for them.
lead to create new root contain the two parts of the old root.

B. Online packet classification

The on-line packet classification contains four main processes: the R-tree query, rule fields extraction, R-tree full fields match, and R-tree updating. Once a packet arrives it will go directly to the R-tree root after creating its corresponding MBR, after R-tree querying an answer set is collected, if this answer set contains more than one match result then the highest priority matched rule is selected and the rest rule fields is extracted from the matched rule’s node to get a full fields match. If a full fields match success, a call for related action is made, otherwise a R-tree update is needed. More details descriptions of these processes are listed in the next sections.

1) R-tree query: The algorithm that processes range queries in an R-tree is given in Algorithm 2. For a rule node entry R, R.mbr denotes the corresponding MBR, C corresponding Concatenated fields with (Port number range PNR and flag F) and R.p the corresponding pointer to the next level. If the node is a leaf, then R.p denotes the corresponding object identifier (oid), Q.mbr denotes the corresponding query MBR. In search step, the same procedure as insertion is performed on incoming packets prefixes in order to convert them into 2-dimensional data. After conversion, using standard searching procedure of R-tree, all overlapping rectangles with query rectangle are found (if any). The the query will start from the root and finds all rectangles that are stored in an R-tree with root node RN which are intersected by a query rectangle. If the root node is not leaf node then a recursive call to range search for each rule entry in that root that intersect the query MBR will made (line 1-5), otherwise(the root or the called node is a leaf node) the procedure of extracting fields will work here for each rule entry that leaf(line 6, 7, and 8). A lookup generates preliminary packet classification results without full comparison between rules and packets, when overlapping rectangles with query rectangle are found. There are another matching procedure (described in next section) in order to make sure that this rectangles are fully matched with query rectangle( line 9-14). If the answer set contains more than one matched rule, the rule with the highest priority selected.

2) Rule fields extraction: In the search algorithm the tree traverse to locate an appropriate leaf to accommodate the query MBR (Q.mbr), for each matched node. If it is not leaf node a recursive call for search algorithm are made, otherwise (it is a leaf node) all entries in that node are examined to find those which R.mbr intersects the query Q.mbr, then, the port number range PNR and flag F should be extracted from that node and the query Q.mbr and a sequential matching is performed. For both R-tree leaf rule data nodes and the query Q.mbr, there are a stored string contains a collected information of each field’s characteristics, by knowing each field length its so easy to extract it. For some fields that can be a wild-card fields a non standard length may be founded, a binary flag is stored in the tale of the concatenated fields string can tell us about those fields which contain non standard length.

3) R-tree full fields match and R-tree update: The full fields match step is designed to report a full matches between incoming packets and rules. It extracts both incoming packet data and rule data and then full match process compares them based on each field’s characteristics (exact, prefix, and range). During the full match process, if the field’s match fails, the full fields match process will move to next search result rule immediately. It retrieves the search result according to their priority, if any match happen, it ignores the remainders results and reports this match. If there is no match (there are no rule match the incoming packet in the ruleset), the full fields match
Range search

Require:

TypeNodeRN, TypeRegionQ, TypeConcatenatedf ieldsC

{Finds all rectangles that are stored in an R-tree with root node RN, which are intersected by a query rectangle Q.mbr. Answers are stored in the set A } 

1: if RN is not a leaf node then 
2: examine each rule entry r of RN to find those r.mbr that intersect Q.mbr 
3: for such rule entry r do 
4: call RangeSearch( r.ptr, Q) 
5: end for 
6: else 
7: examine all entries r and find those for which r.mbr intersects Q 
8: extract Port-number-ranges(PNR), Flag F from C 
9: if ( r.C.PN ∈ PNR) then 
10: for each character in C do 
11: if r.C[Counter] = 
12: C[Counter] or Flag[Counter] = 1 then 
13: add these entries to the answer set A 
14: end if 
15: end for 
16: end if 

process conducts the default action (contains a ruleset update in most case). If a ruleset update is needed, the controller will generate a new rule to get an action for such unmatched packets, and to made this update to the ruleset a new regular insertion call for this new rule have to made.

C. Theoretical Analysis

In this section, the time and space complexities are given for the proposed solution to show how our proposed solution reduces the complexity by using R-tree lookup. Assume that there are N rules in a ruleset R, and each rule has H fields in it. For this ruleset, and each field has up to K bits in it, then the time complexity for lookup algorithm for R-tree of M degree is:

\[
\text{Time complexity} = \log M N + H \times K = O(\log M N)
\]

The space complexity for our proposed algorithm for the leaves nodes is:

\[
\text{Space complexity (leaves nodes)} = H \times K \times N.
\]

And for tree inner nodes (each node contains only 2 prefix fields):

\[
\text{Space complexity (inner nodes)} = (\log M - 1)N \times N \times 2 \times K.
\]

Then the total space complexity for our propose tree structure equals:

\[
\text{Space complexity (total)} = H \times K \times N + (\log M - 1)N \times N \times 2 \times K = O(N \log M N).
\]

Table III depicts the specification of our simulation rulesets and tracing data type, size, and specifications.

| Rule set type | NO. of rule | Specifications |
|---------------|-------------|----------------|
| ACL 1 K      | 916         | medium overlapping, high wildcard |
| ACL 5 K      | 4417        |                |
| ACL 10 K     | 9602        |                |
| IPC 1 K      | 937         | low overlapping, low wildcard |
| IPC 5 K      | 4459        |                |
| IPC 10 K     | 9037        |                |
| FW 1 K       | 790         | high overlapping, medium wildcard |
| FW 5 K       | 4652        |                |
| FW 10 K      | 9602        |                |
| Input Tracing| 100,1k, 10k Packets |                |

(H, K are constant values).

As a comparison to the other packet classification algorithm, these complexity is a reasonable, Table III depicts a complexity comparison with well known many-fields packet classification algorithms.

IV. RESULTS

In this section, the experimental results are given to show the feasibility and effectiveness of our proposed algorithm with the comparison along with other existing many-field packet classification solutions.

A. Experimental results

A performance evaluation have been performed on simulated rulesets created by Class-bench tool, which is widely used in evaluating the performance of packet classification algorithms, in these simulations, two prefix fields had been used for building the R-tree and the remaining fields including the port ranges and some required flags had been stored as a single field of string type and appended as a node entries (only on the leaves). Three types of 15 fields rulesets have been generated: access control list (ACL), IP chain (IPC), and firewall (FW) with three sets for each type contain 1000, 5000, and 10000 rules respectively. All rulesets have less than 10% wild-cards ratio which is the normal rulesets wild-cards ratio. All experiments are conducted on an Intel Core i7 CPU machine with 4GB DDR2 RAM as the main memory. This machine is equipped a NVIDIA Quadro FX 880M GPU. Table IV depicts the specification of our simulation data rulesets and tracing packets.
average latency and throughput for these rulesets for up
time to classify a single packet, Table V depicts our approach
in packet per second(PPS), the latency as the average required
number that our approach can classify in one second measured
throughput.

ACL rulesets requires average lookup time and has average
(ACL) rulesets have the least overlapping rules but it has
requires less than 24 microseconds. The access control list
which is the maximum latency, and rulesets of type IP chain
type Firewall have up to 37 microseconds average latency,

system throughput. Hence, the previ ous reasons, rulesets of
that minimizes the total matching time and maximizes the
of 10%, and less overlapping rules. The R-tree that contains
more overlapping rules can give more querying results and
that takes more lookup time, also the matching rule may
exists on different branch of the tree that makes the less
overlapping rule the best throughput case. Conversely, the
more wild-card ratio the best throughput case because of the
wild-cards fields need no extracting and matching process,
that minimizes the total matching time and maximizes the
system throughput. Hence, the previous reasons, rulesets of
type Firewall have up to 37 microseconds average latency,
which is the maximum latency, and rulesets of type IP chain
requires less than 24 microseconds. The access control list
(ACL) rulesets have the least overlapping rules but it has
least wild-cards. Hence, the results show that the R-tree of
ACL rulesets requires average lookup time and has average
throughput.

We had take increasing amount (100, 1000, 10000, 100000)
of tracing packet that has been selected randomly from pre-
viously generated 100,000 tracing packets, and then we test
our system when lookup for this varying amount of tracing
packets on our simulation varying type and size rulesets, and
the results show as can be seen in Fig. 6(a), that the minimum
average required lookup time was for looking-up on rulesets
of type IPC and the worst was for looking-up on rulesets of
type FW. It is the same results as in Fig 6(b).

Our proposed packet classification algorithm has developed to
be to maintain scalability with the increasing rulesets size and
field number in a ruleset, and designed to analyze the average
number of memory accesses and the maximum number of
memory accesses required to perform packet classification and
to calculate the memory requirement. We have evaluate our
proposed system required memory accesses in both average
and worst case on R-tree of degree (M =4, m=2) and perform a
comparison with other many-fields packet classification
algorithms such as (H-trie [31], AQ7 [32], PQT [3], bit-vector
(BV)[19], and HyperCuts [26]). The comparison results is
depicted in Table VI, which show that our proposed algorithm
has the almost the best memory access in both average and
worst cases(most of compared algorithms work on two field
ruleset, that makes our proposed 15 field packet classification
algorithm seems bad in this aspect).

As depicted in Table IV, our simulation rulesets have
varying characteristic. And therefore, our proposed approach
performs differently on different rule type as depicted in
Fig. 5, that the highest throughput that our system is achieved
when working on IP chain (IPC) rulesets as a result of the
low overlapping rules in that ruleset type , and the worst-case
scenario for all rulesets type is when working on firewall
(FW) rulesets as a result of the high overlapping rule in that
ruleset type and low wild-cards ratio around of 7.9%. On the
other hand, IPC rulesets have more wild-cards ratio around
of 10%, and less overlapping rules. The R-tree that contains
more overlapping rules can give more querying results and
that takes more lookup time, also the matching rule may
exists on different branch of the tree that makes the less
overlapping rule the best throughput case. Conversely, the
more wild-card ratio the best throughput case because of the
wild-cards fields need no extracting and matching process,
that minimizes the total matching time and maximizes the
system throughput. Hence, the previous reasons, rulesets of
type Firewall have up to 37 microseconds average latency,
which is the maximum latency, and rulesets of type IP chain
requires less than 24 microseconds. The access control list
(ACL) rulesets have the least overlapping rules but it has
least wild-cards. Hence, the results show that the R-tree of
ACL rulesets requires average lookup time and has average
throughput.

In this paper, we propose a many field packet classification
algorithm by using R-tree structure to improve the system
performance. The proposed method converts a huge and biased
TABLE V
THE PROPOSED APPROACH THROUGHPUT AND LATENCY FOR DIFFERENT TYPE AND SIZE OF RULESETS.

| Ruleset type | 100 incoming packets | 1000 incoming packets | 10000 incoming packets | 100000 incoming packets | Throughput packet/s |
|--------------|-----------------------|------------------------|------------------------|------------------------|---------------------|
| FW 100       | 24.2378               | 24.06405               | 23.619935              | 26.7730916             | 38832               |
| FW 1000      | 25.7154               | 30.44346               | 32.648207              | 32.5784345             | 30692               |
| FW 5000      | 34.5191               | 34.51149               | 35.154708              | 34.6439483             | 38263               |
| FW 10000     | 35.1021               | 34.2533                | 34.17682               | 35.4241835             | 37265               |
| IPC 100      | 24.1243               | 24.17178               | 25.318351              | 24.6959593             | 40492               |
| IPC 1000     | 27.5183               | 27.20913               | 26.896741              | 27.5367645             | 36315               |
| IPC 5000     | 28.886                | 29.96238               | 29.018201              | 29.1298734             | 34584               |
| IPC 10000    | 29.9885               | 31.65096               | 29.1298734             | 34329                  |                     |
| ACL 100      | 25.1123               | 26.48657               | 26.040894              | 26.3841595             | 37265               |
| ACL 1000     | 27.3183               | 27.20913               | 26.365184              | 27.5367645             | 36315               |
| ACL 5000     | 27.4964               | 28.40572               | 28.665517              | 29.814487              | 34584               |
| ACL 10000    | 29.3885               | 31.65096               | 29.1298734             | 34329                  |                     |

Fig. 6. (a) Latency average for different rulesets types and size, (b) Required lookup time for different amount of tracing data.

rule space into rectangular data and organize it as R-tree structure in a way so that each branch of the R-tree contains a group of rules that shares the same specification and each group is referred to M subgroups and so on, that gives as a way to fast processing and easy updating. The proposed data structures were designed to improve the many fields packet classification performance and give better latency task for a better system performance. The proposed solution was examined with simulated class-bench rulesets with all key factors related to system performance. A comparison with well known many-fields packet classification algorithms have been made to show the effectiveness of our approach.

REFERENCES
[1] F. Baboescu, G. Varghese Scalable packet classification, ACM SIGCOMM Computer Communication Review 31, no. 4, 2001: 199-210. Harvard
[2] N. Beckmann, H. Kriegel, R. Schneider, and B. Seeger, The R*-tree: an efficient and robust access method for points and rectangles. Vol. 19, no. 2. ACM, 1990.
[3] M. Buddhikot, S. Suri, and M. Waldvogel, Space decomposition techniques for fast layer-4 switching, Springer US, 2000.
[4] M. Casado, N. Gude, J. Stirling, L. Poutievski, M. Zhu, and R. Ramanathan, Onix: A Distributed Control Platform for Large-scale Production Networks, In OSDI, vol. 10, pp. 1-6, 2010.
[5] R. Cohen, D. Raz Simple efficient TCAM based range classification, In INFOCOM, 2010 Proceedings IEEE, pp. 1-5. IEEE, 2010.
[6] M. Dixit, B. Barbadekar, and A. Barbadekar, Packet classification algorithms, In Industrial Electronics, 2009. ISIE 2009. IEEE International Symposium on, pp. 1407-1412. IEEE, 2009.
[7] M. Faezipour, M. Nourani, Wire-speed TCAM-based architectures for multimatch packet classification, Computers, IEEE Transactions on 58, no. 1, 2009: 5-17.
[8] H. Farhadi, A. Nakao, Rethinking flow classification in sdn, In Cloud Engineering (IC2E), 2014 IEEE International Conference on, pp. 598-603. IEEE, 2014.
[9] N. Foster, A. Guha, M. Reitblatt, A. Story, M. Friedman, N. Katta, and C. Monsanto, Languages for software-defined networks, Communications
| Metrics | Rulesets | No. of rules(N) | proposed | TPBF | TSP | H-trie | Area-based quad-trie | Priority based quad-trie | Bit vector |
|---------|----------|----------------|----------|------|-----|--------|---------------------|------------------------|------------|
| Memory requirement (Kbytes) | ACL 1k | 902 | 552 | 22.1 | 62.8 | 82.9 | 56.4 | 29.9 | 153.3 |
| | ACL 5k | 4,660 | 2,648 | 174.2 | 273.2 | 401.5 | 200.2 | 145.6 | 2,793.0 |
| | ACL 10k | 9,660 | 5,812 | — | — | — | — | — | — |
| | IPC 1k | 972 | 604 | 23.0 | 63.8 | 121.6 | 71.2 | 30.9 | 154.3 |
| | IPC 5k | 4,468 | 2,720 | 172.7 | 184.2 | 224.7 | 254.3 | 139.9 | 2,531.0 |
| | IPC 10k | 9,036 | 5,548 | — | — | — | — | — | — |
| | FW 1k | 852 | 540 | 22.0 | 42.9 | 39.4 | 35.2 | 27.2 | 111.9 |
| | FW 5k | 4,351 | 2,864 | 170.3 | 172.1 | 119.1 | 479.8 | 136.0 | 2,340.0 |
| | FW 10k | 9,309 | 6,296 | — | — | — | — | — | — |
| Memory accesses per packet (average) | ACL 1k | 902 | 6 | 6.48 | 17.5 | 77.2 | 38.6 | 35.6 | 66.0 |
| | ACL 5k | 4,660 | 7 | 11.4 | 19.2 | 84.0 | 50.1 | 59.6 | 64.1 |
| | ACL 10k | 9,660 | 8 | — | — | — | — | — | — |
| | IPC 1k | 972 | 6 | 7.90 | 27.8 | 71.9 | 94.5 | 73.6 | 63.6 |
| | IPC 5k | 4,468 | 7 | 18.7 | 36.3 | 85.6 | 344.8 | 202.1 | 151.9 |
| | IPC 10k | 9,036 | 8 | — | — | — | — | — | — |
| | FW 1k | 852 | 6 | 33.6 | 45.4 | 52.1 | 369.3 | 197.9 | 196.6 |
| | FW 5k | 4,351 | 7 | 39.5 | 44.2 | 69.2 | 660.5 | 571.1 | 738.8 |
| | FW 10k | 9,309 | 8 | — | — | — | — | — | — |
| Memory accesses per packet (worst case) | ACL 1k | 902 | 8 | 55 | 65 | 624 | 64 | 75 | 68 |
| | ACL 5k | 4,660 | 10 | 59 | 59 | 177 | 94 | 115 | 76 |
| | ACL 10k | 9,660 | 11 | — | — | — | — | — | — |
| | IPC 1k | 972 | 8 | 19 | 42 | 128 | 119 | 106 | 80 |
| | IPC 5k | 4,468 | 10 | 40 | 65 | 192 | 415 | 295 | 230 |
| | IPC 10k | 9,036 | 10 | — | — | — | — | — | — |
| | FW 1k | 852 | 8 | 75 | 93 | 117 | 444 | 293 | 318 |
| | FW 5k | 4,351 | 10 | 85 | 89 | 146 | 1193 | 999 | 1,044 |
| | FW 10k | 9,309 | 10 | — | — | — | — | — | — |

Table VI: The performance comparison to the other algorithms.
Fig. 7. Memory accesses per packet (average) comparison to the other algorithms. Memory accesses per packet (worst case) comparison to the other algorithms.

[34] P. C. Wang, D. Y. Chang, *TCAM-Based Multi-Match Packet Classification Using Multidimensional Rule Layering*, IEEE/ACM Transaction on Networking, 2016, 24.2: 1125-1130.