IP Packet Forwarding Based on Comb Extraction Scheme

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Abstract—**In this paper, we present an efficient IP packet forwarding technique and its architecture. One forwarding table is decomposed into two balanced smaller sub-forwarding tables by a novel splitting rule. Therefore, an IP lookup can be converted into a pair of small sub-lookups. The output of an incoming packet can be determined by comparing the information, attached to the matching sub-prefixes of both sub-lookups. The sub-lookups and information comparison can perform in parallel. Our approach not only speeds up the Best Matching Prefix (BMP) search, but also reduces storage space at the same time.**

Keywords-IP address lookup

I. INTRODUCTION

The major function of a router is to forward packets. Since the Internet traffic increases rapidly, speeding up the link rate is required in order to provide good service [1]. It is difficult to make the performance of a router keep up with this increasing demand. In particular, the address lookup operation is a major problem.

Many lookup algorithms create a data structure that takes advantage of the binary search tree method, which is among the mature search algorithms [2]. The binary trie [3] method and its variations including Patricia trie [4], multibit trie [5] and LC trie [6] have been presented in the literature. Some heuristic approaches were designed to facilitate the use of binary trees [2], such as search on prefix range [7,8] and search on prefix length [9]. Unfortunately, these approaches usually suffer from large storage requirements or poor updating features. In addition, some hardware-based solutions are proposed by using a large DRAM for the entire forwarding table [10]. Using CAM is also presented in [11]. A good survey of these methods can be found in [12].

The main contribution of this paper is two-fold. First, a forwarding table is decomposed into a pair of balanced sub-tables by using the Comb Extraction Scheme (CES). The two independent search processes can work simultaneously. In order to determine the output port the packet should be sent to, the comparison of information pairs, attached to those matching sub-prefixes in both sub-tables, needs to be executed in the end. CES can reduce storage space, speed up search time, alleviate distribution dependent problems, and minimize information comparison load. Secondly, we propose an efficient architecture to realize this methodology. The flexibility of this architecture allows IP address lookup to be easily integrated within routing SoCs and generic network packet processing units.

TABLE I. A SAMPLE FORWARDING TABLE

Index	**Prefix**	**Len**	**Port**
1	**11000110100110***	14	1
2	**11000110011***	11	1
3	**11000110010***	11	1
4	**1101011100001011***	16	1
1	**1100011001***	10	2
2	**011110000011***	12	2
3	**11000110100***	11	2
4	**10001010110011***	14	2
5	**100010101011***	12	2
6	**1110111101***	10	2
7	**01111000101***	11	2
8	**0111100011100***	13	2
1	**1100011010011010***	16	3
2	**1100011001110***	13	3
3	**1000101011001***	13	3
4	**01111000001110***	14	3

In this paper, we focus on the unicast (single-source, single-destination) routing of backbone routers. In an IP forwarding table, an entry usually has this structure: <*DesPrx, PrxLen, ForInf*>. *DesPrx* is the Destination Prefix, *PrxLen* is the length of the prefix, and *ForInf* usually is a next hop address or an output port number, respectively. Suppose $P = \{p_1, p_2, \cdots, p_M\}$ is the set of M prefixes with N outputs recognized by a router. When examining the forwarding tables carefully, we can find that the number of distinct next hops in a routing table is very small, comparing with the tens of thousands of prefixes. It is shown clearly in sample Table 1 (only 3 ports for 16 entries). All the entries are sorted in terms of the ports, and the index is a number to distinguish between entries sharing the same port.

II. NEW DATA STRUCTURE

For IPv4, an IP address A is 32-bit long. It can be decomposed into two 16-bit long sub-sequences by the following strategy: From the left-most bit to the right-most bit, all the bits in the odd positions are extracted to form sub-sequence α, and all the bits in the even positions are extracted to form sub-sequence β. We call this splitting approach the Comb Extraction Scheme (CES). For example, consider the following IP address in binary bits, **1**0**1**0**0**0**0**1 **0**0**1**1**0**1**1**0 **1**1**0**1**0**0**0**0 **1**1**1**0**1**0**0**1. After the decomposition, α and β will be 1100010110001110 and 0001011011001001, respectively. Similarly, a prefix also can be decomposed into two sub- sub-prefixes α and β. Both of them end by the wildcard *.

TABLE II. SUB-FORWARDING OF TABLE 1 (EXTRACTING BITS IN ODD POSITIONS)

Index	Sub-Prefix	Len	Port Indicator	Forwarding Information
1	011001*	6	010	2(2)
2	0110011*	7	001	3(4)
3	011011*	6	010	2(7)
4	0110110*	7	010	2(8)
5	10010*	5	010	2(1)
6	100100*	6	100	1(3)
7	10010011*	8	100	1(4)
8	100101*	6	100	1(2)
9	1001010*	7	001	3(2)
10	100110*	6	010	2(3)
11	1001101*	7	100	1(1)
12	10011011*	8	001	3(1)
13	1011101*	7	011	2(4), 3(3)
14	101111*	6	010	2(5)
15	11110*	5	010	2(6)

TABLE III. SUB-FORWARDING OF TABLE 1 (EXTRACTING BITS IN EVEN POSITIONS)

	Sub-Prefix	Len	Port Indicator	Forwarding Information
1	000001*	6	010	2(5)
2	000010*	6	001	3(3)
3	0000101*	7	010	2(4)
4	10100*	5	010	2(3)
5	1010010*	7	100	1(1)
6	10100100*	8	001	3(1)
7	10101*	5	110	2(1), 1(2), 1(3)
8	101011*	6	010	3(2)
9	10111*	5	010	2(6)
10	11000*	5	010	2(7)
11	110001*	6	010	2(2)
12	1100010*	7	001	3(4)
13	110010*	6	010	2(8)
14	11110001*	8	100	1(4)

Hence, a forwarding table can be converted into two extended sub-forwarding tables. Table 2 and Table 3 are the examples of the pair of sub-forwarding tables of Table 1. Each sub-entry has the same structure <sub-prefix, length, port-indicator, forwarding information>.

In Table 2 and Table 3, the ***Forwarding Information*** not only contains the information of the port number, but also contains the information of the corresponding index based on the port in Table 1. It is composed of a set of **forwarding units** *a(b)*, which implies that, in Table 1, the original prefix of this sub-prefix is forwarded to port *a,* and the corresponding index is *b*. In general, the forwarding information of each sub-entry in a sub-table consists of several forwarding units. For example, the sub-prefix of the 7th entry in Table 3 is 10101*, which collects the information of the original prefixes whose bits in the even positions are 10101*. It contains three forwarding units, 2(1), 1(2), and 1(3). Usually, a core router has no more than 128 output ports. So the length of port can satisfy that $len(port) \le 7$ in bits. Therefore, a 20-bit long sequence is enough to represent a forwarding unit, leaving 13 bits for the index (up to 8,12 entries could have the same port).

In a sub-table, a N- bit ***port indicator vector*** is attached to every sub-entry. A bit i is set in the bit vector if and only if the i^{th} port occurs in its forwarding information. Usually the width of it is no more than 128. The total storage cost for the extra information is shown in last column in Table 4.

What is the benefit of the CES approach? Primarily, one lookup will be divided into a pair of shorter and parallel sub-lookups. Can CES make the two sub-lookups balance the time access and the memory consumption? After the two parallel sub-lookups, some sub-prefixes will match the pair of sub-search key. In order to find the BMP, we need to combine the results, comparing the information of any reasonable pair of matching sub-prefixes from both sub-lookups. This leads to the next question: can CES cause heavy comparison loads, which will cost extra time? We discuss this point in the rest of the section.

Firstly, let us point out that CES makes the entries of the pair of sub-tables well distributed.

In comparing two bit patterns, the Hamming distance is the count of bits different in the two patterns. Here, we give a new definition to determine the distance between two prefixes, which is similar to the Hamming distance.

Definition 1: Let a and b be two prefixes in a table. $|a|$ and $|b|$ represent their lengths. Let $ML = \min(|a|,|b|)$. We define the **Pseudo-Hamming Distance** (PHD) between two prefixes as:

$$PHD(a,b) = \sum_{i=0}^{ML} (L-i)\,|a_i - b_i|,$$ where a_i and b_i are the left-most i^{th} bits of a and b, and L is the maximum length of sequences (In IPv4, L in the original forwarding table is 32, 16 for sub-forwarding tables). Let *MPHD* be the mean of PHD of any two different prefixes in one table. PHD is affected by both the number of bits that are not identical, and their positions. For example, let us assume a, b and c are 011001*, 0110010*, and 10010011* respectively. Let L be 16. Then: $PHD(a,b) = 0$, $PHD(a,c) = 69$, and $PHD(b,c) = 79$.

Lemma: Let a and b are two prefixes. If one is a prefix of the other, then $PHD(a,b)$ equals to zero.

TABLE IV. PERFORMANCE OF SUB-TABLES BY USING THE CES

	Entries		Sub-entries	MPHD	MPL	Max(BLFI)	MLFI	SDFI	CCF	Storage Cost (in Byte)
Mae-east	47206	Sub-table 1	4026	55.22	11.18	93	11.73	13.41	8	186.06K
		Sub-table 2	5341	56.56	11.18	86	8.84	9.71		209.15K
Mae-west	77002	Sub-table 1	5703	56.47	11.22	100	13.05	15.49	8	270.81K
		Sub-table 2	6989	57.84	11.22	78	11.02	12.57		241.95K
Aads	63980	Sub-table 1	5689	56.80	11.35	110	11.25	14.28	8	245.14K
		Sub-table 2	6735	57.45	11.35	89	9.50	10.84		261.44K
Paix	22116	Sub-table 1	4077	54.59	11.15	40	5.42	5.35	7	117.65K
		Sub-table 2	4704	55.67	11.15	28	4.70	4.23		127.48K

TABLE V. PERFORMANCE OF SUB-TABLES BY SUCH A SPLITTING RULE: EXTRACTING THE HIGHER 16 BITS TO FORM SUB-TABLE 1 AND EXTRACTING THE LOWER 16 BITS TO FORM SUB-TABLE 2

	Entries		Sub-entries	MPHD	MPL	Max(BLFI)	MLFI	SDFI
Mae-east	47206	Sub-table 1	6939	59.85	16.00	280	6.80	13.63
		Sub-table 2	1349	43.24	6.47	2735	34.99	93.62
Mae-west	77002	Sub-table 1	10794	23.32	16.00	253	7.13	15.33
		Sub-table 2	1692	51.63	4.79	5939	45.50	164.45
Aads	63980	Sub-table 1	8314	61.54	16.00	465	7.69	16.65
		Sub-table 2	3540	49.03	9.94	3385	18.07	73.38
Paix	22116	Sub-table 1	4540	59.68	16.00	128	4.87	7.98
		Sub-table 2	1238	48.85	5.03	1406	17.86	49.95

The value of MPHD can stand for the distribution of entries in a table. If MPHD is large, it implies that, in a trie of a forwarding table, nodes spread widely, rather than just focus on several deep branches. This allows for a faster search. CES is almost the best of splitting rules to maximize the MPHD of each sub-table, and there is not much variance between the two values, which implies that CES leads to a balanced distribution of entries in the two sub-tables.

Secondly, CES also balances the sub-prefix lengths in the two sub-tables.

Definition 2: Let the **Mean Prefix Length** (MPL) in any sub-table be expressed by: $\frac{1}{M}\sum_{i=0}^{SM} n_{IFO}^{i} Len_i$, where M is the number of entries in the original forwarding table, SM is the number of sub-entries in this sub-table, n_{IFO}^{i} is the number of forwarding units attached to the i^{th} sub-entry, and Len_i is the length of it.

Let *a* be an original prefix in a forwarding table. After having been decomposed, it will be converted into two sub-prefixes, named a_1 and a_2. The difference between the lengths of a_1 and a_2 satisfies the inequality: $0 \le |a_1| - |a_2| \le 1$. In other words, CES is an efficient way to enable the search in the pair of sub-tables to keep in pace with the lookup.

Thirdly, CES makes the forwarding units well distributed in each sub-table.

Definition 3: (1) The **Basic load of Forwarding Information** (BLFI) of i^{th} sub-entry in each sub-table is defined as the total number of forwarding units in the i^{th} sub-entry.

(2) The **Mean load of Forwarding Information** (MLFI) of sub-entries in each sub-table is defined by $\frac{1}{SN}\sum_{i=1}^{SN} BLFI_i$, where SN is the total number of sub-entries in this sub-table.

(3) The **Standard Deviation of Forwarding Information** (SDFI) of sub-entries in each sub-table is defined by $\sqrt{\frac{1}{SN}\sum_{i=1}^{SN}(BLFI_i - MLFI)^2}$.

These metrics are significant when analyzing CES's performance. Their desirable values should be as low as possible. Whether the comparing time between sub-prefixes in the second phase is reasonable or not depends on these three values. In our small example, $MLFI_1 = 1.067$, $MLFI_2 = 1.143$, $SDFI_1 = 0.25$, and $SDFI_2 = 0.51$.

Fourthly and finally, CES balances the comparison cost.

Definition 4: The **comparison cost factor** (CCF) is used to judge whether the comparison load of those matching sub-prefixes in two sub-tables for an address lookup next is heavy or not. CCF is a statistical value from experiments, by counting the pairs for which a comparison was really needed.

Actually, it is not necessary to compare every pair of matching sub-prefixes, for there are constraints among the matching sub-prefixes, once they are the final ones we are looking for. We know that if a_1 and a_2 are two the final matching sub-prefixes in the two-tables for an address, then they should satisfy the following: (1) $|a_2|$ only can be equal to $|a_1|$ or $|a_1| - 1$; (2) In the two corresponding port indicator vectors, $\exists i, i < N, \mathrm{PIV}_i^1 = \mathrm{PIV}_i^2 = 1$. (where PIV is the port indicator vector).

Only if the matching sub-prefixes a_1 and a_2, which come from different sub-tables, meet the demands above, comparison is needed. CCF is a parameter to observe the number of pairs which satisfy the conditions, and need to execute real comparison. Anyway, CCF has its upper bound: Let $MinNum = \min(Num_1, Num_2)$, where Num_1 and Num_2 are the numbers of matching sub-prefixes of the two sub-tables. Then: $CCF \le 2 \times MinNum$.

Table 4 and Table 5 give us the performances of sub-tables by using different splitting rules respectively. It is clear that the CES is much better than the other one (extracting the higher 16 bits to form sub-table 1 and extracting the lower 16 bits to form sub-table 2).

III. COMPARISON SET

In this section, we describe how to analyze the matching sub-prefixes from two sub-tables, in order to find the common matching prefix. This part can be implemented in an ASIC.

TABLE VI. COST FOR COMPARISON/MATCHING SUB-PREFIX

	Entries	Average delay (ns)	Delay(80% of comparisons) (ns)	Worst case (ns)
Mae-east	47206	1.39	<8.58	36.9
Mae-west	80000	3.04	<12.87	56.5
Aads	63980	2.74	<9.06	54.5
Paix	22116	0.40	<1.55	5.26

The first step is to decide whether further comparing is necessary, which has already been explained above. The second step is to compare the forwarding units, only when the first step succeeds.

If $P1_i$ and $P2_j$ are two matching sub-prefixes of the pair of sub-tables, each of them contains a set of forwarding units. We need to compare every unit in a set with the all the units in another set, if the port numbers attached belong to the set of common port numbers. Let $Info1_i$ and $Info2_j$ be the information sets of $P1_i$ and $P2_j$, which contain $M1$ and $M2$ such information units. Therefore, for each comparison, $M1 \times M2$ pairs of comparison units are needed.

In the comparison between $Info1_i$ and $Info2_j$, if there exists an exact match in one comparison unit, it implicates that $P1_i$ and $P2_j$ are the right decomposition parts of an original prefix in a forwarding table.

Lemma: In the comparison between $Info1_i$ and $Info2_j$, there at most exists one exact match in all pairs of comparison units.

Proof: Assume that there exists two pairs of units, ($Info1_{i,k}$, $Info2_{j,m}$) and ($Info1_{i,l}$, $Info2_{j,n}$), which match exactly. That is, $Info1_{i,k} = Info2_{j,m}$, and $Info1_{i,l} = Info2_{j,n}$. It means that in the original forwarding table, there are two entries, which have the same prefix, but will be forwarded to different ports. It is impossible for unicast. As a consequence, the assumption is not right, which means that there at most exists one exact match in all pairs of comparison units.

Since each forwarding unit is 20 bit long, based on present-day technology, VLSI feature size of $\lambda = 0.13\mu m$, it is possible to input 5 forwarding units of each matching sub-prefix at the same time, allowing 25 comparison units to work in parallel. Therefore, all comparison units work in serial to the end until there is a comparison unit exact match. The delay of every 25 parallel comparisons is 250ps. Table 6 shows the time cost for comparing every forwarding unit of two matching sub-prefixes. We find that this time increases when the forwarding table's size increases. Actually, the real cost is smaller than this, since the comparison stops when there exists an exact match. Although the cost of most cases is small, the worst case is not good enough.

IV. ARCHITECTURE OF THE NEW ALGORITHM

Fig. 1 describes a rough picture on how this system works. We provide two structures based on CES.

A. *CES + Index tables*

The maximum length of the entries is sharply reduced due to CES. The size of the array is 2^{16} for IPv4. Each entry of the array has the structure: {length[4], port-indicator[128], pParent[16], pInformation[16] }, in which, pParent is the pointer to its parent, the most specific prefix of it, and pInformation is the pointer to its forwarding information.

Each main index table consumes 1.28Mbytes, however the additional table for forwarding information is small (memory cost is shown in Table 4). The total memory consumption is about 3Mbytes. It is not scalable to IPv6, for the size of the index table is 2^{64}, which is still impossible for current technology.

B. *CES + Binary Trie*

The binary trie is a basic structure in IP lookups. A forwarding table is decomposed into a pair of half-level sub-tables. The storage cost for two 16-level tries is much smaller than one 32-level trie. Table 7 gives the memory cost when we use CES + Binary trie, smaller than when only binary trie is used. Most memory is consumed at the nodes with forwarding information. The updating time is $O(\frac{W}{2})$, where W is the prefix length.

Different architectures of a sub-table will lead to different search strategies.

If CES + Index table is used, when a search starts, the first sub-prefixes we reach in two sub-tables are the longest matching sub-prefixes. Not only is the forwarding information of both of them sent to the comparison set, but also they will point to their own most specific parent rows, and output another pair of forwarding information to compare. But now the lengths of sub-prefixes are shorter than the former ones. Therefore once there is an exact match in the comparison set, the search stops. The average comparison times in our experiments were 1.272, so the average of total delay in comparison is not more than 8ns (if the total entries are not more than 80K).

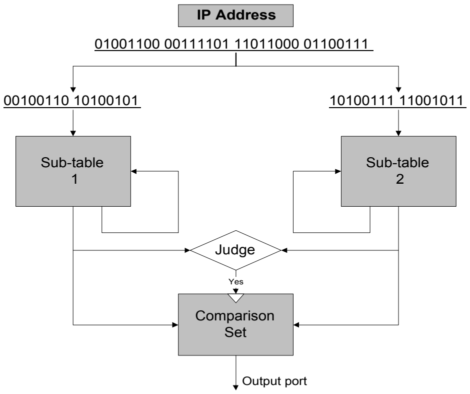
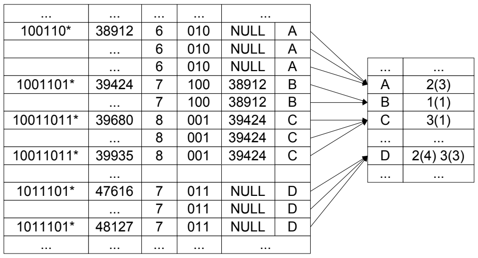


Figure I. The Architecture of the System



...	...	...	...	...	
100110*	38912	6	010	NULL	A
	...	6	010	NULL	A
	...	6	010	NULL	A
1001101*	39424	7	100	38912	B
	...	7	100	38912	B
10011011*	39680	8	001	39424	C
	...	8	001	39424	C
10011011*	39935	8	001	39424	C
	...				
1011101*	47616	7	011	NULL	D
	...	7	011	NULL	D
1011101*	48127	7	011	NULL	D
...	...	...	...	...	

...	...
A	2(3)
B	1(1)
C	3(1)
...	...
D	2(4) 3(3)
...	...

Figure II. The Structure of CES + Index tables

If CES + Binary tries is used, when a search starts, the first matching sub-prefixes we reach in two sub-tables are the shortest. We need to do the comparison of their forwarding information, and on the same time, we need to continue traversing the sub-tries until they are exhausted. The last exact match is the final output port of this IP packet. The total average delay in comparison is no more than 25ns, since the CCF is less than 8 (if the total entries are not more than 80K).

TABLE VII. STORAGE COST COMPARISON (CES+BINARY TRIE *VS* BINARY TRIE) (IN BYTE)

Storage Cost	**Mae-east**	**Mae-west**	**Aads**	**Paix**
Sub-table1	215.5K	310.2K	285.6K	147.8K
Sub-table2	247.2K	288.9K	308.3K	161.6K
Original Table	1295.3K	2003.8K	1657.8K	718.8K

There is a pipeline benefit, no matter which architecture we use: the comparison set works when both sub-lookups are preparing for the next pair of comparing sub-prefixes. From the experiment, we can see that the comparison set is fast enough not to be a speed bottleneck, if the forwarding table is not too big.

V. CONCLUSION

We proposed a new methodology and architecture for IP address lookup. Our approach advocates decomposing a forwarding table into a pair of sub-forwarding tables using CES. Comparison is only needed for the reasonable matching sub-prefixes of the two sub-tables. Two sub-lookups and comparison can work in parallel, which provide a new way to speed up the average search time efficiently to handle OC-192 line rates (10 Gb/s).

Unfortunately, with the size of a forwarding table increasing, the forwarding units attached to a sub-prefix increases. If both comparing sub-prefixes carry hundreds of forwarding units, the comparison delay will affect the performance of the whole system. CES cannot improve the performance in worst cases, but can make a big improvement for the average search time. There are lots of potentials to improve performance of comparison set, when the load is heavy. The authors will focus on solving this problem in the future.

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