A Survey on Network Forwarding in Software-Defined Networking

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Abstract

The packet forwarding behaviour of a network relies on the forwarding rules residing in the networking element (e.g. switches and routers) to forward packets. This applies to both traditional networking and software-defined networking (SDN). These forwarding rules vary in their structures and sizes, but they represent the same fundamental functionality: to match incoming packets against rules and determine its forwarding behaviour. All these rules in a network device constitute a packet forwarding pipeline. This survey paper presents a new taxonomy for the representation of the forwarding pipeline in SDN based on core networking functionality. The new taxonomy uses a typology and attributes of the forwarding behaviour to establish a cohesive vocabulary and a classification system to study and characterise the interactions of FTE along an end-to-end path in SDN. The survey also shows that Boolean algebra is most widely used for the low-level representation of FTEs and facilitates the assessment of "equivalence" between FTEs and has practical uses in traffic monitoring and packet classification within SDN, among others.

Keywords: Software-Defined Networking (SDN), Forwarding Table Entry (FTE), Forwarding Pipeline, Forwarding Representation, Networking Element, Boolean Algebra

1. Introduction

Networking elements in a computer communication network are forwarding devices (switches or routers) linked together to deliver packets from one point to another. In a traditional network (e.g. Internet Protocol (IP) and MPLS (Multi-protocol label switching), these networking elements have a control plane and a data plane coupled together [1]. The control plane performs control functions such as deciding the best routing (or forwarding) path, installing rules for forwarding and configuration of networking elements along the end-to-end path. While the data plane forwards packets based on forwarding rules made by the control plane.

The forwarding rules in traditional networking are defined as access control list (ACL) and IP lookup table. The ACL is mostly configured by the administrator manually while IP tables are usually created and updated locally by the routing protocol residing in each networking element [2, 3]. Often, the ACL and IP tables are modified manually by network administrators to manage localized requirements resulting in a complex network configuration. In addition, the use of a low-level programming language and vendor dependency makes configuration of the network cumbersome and error prone for network operators.

To simplify the configuration complexity in the traditional network, a new networking paradigm called Software-Defined Networking (SDN) that uses a high-level programming language has emerged [4, 5]. SDN is a network paradigm in which the control plane is decoupled from a networking element. In an SDN, the control function is moved to a logically centralised controller which eases the load on a networking element with the primary function of forwarding packets. It allows the network to be controlled and managed through a software written in a high-level programming language.

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The shift of the control function from a hardware to software dependency allows the system to be more agile, programmable and centrally managed. The forwarding rules in an SDN are defined by a set of flow table and group tables, the difference between flow tables and group tables is that Group tables consist of multiple flow table entries and actions associated with particular groups (as defined by the controller). In the remainder of this paper, we generalize flow tables and group tables as forwarding table entries (FTEs), except where it is necessary to differentiate them.

Forwarding table entries have more flexible structure, stronger forwarding manipulation abilities and inevitably more complicated logic than the ACL and IP tables. These dynamically provisioned FTEs control packet forwarding behaviour from a network-wide perspective rather than the device-level perspective in ACLs and IP tables [6]. To model the network-wide forwarding behaviour, a controller must have a systematic method to represent FTEs across the network. Moreover, a common vocabulary and representation (or model) of FTEs is necessary to systematically model end-to-end network behaviour and abstract low-level-behaviour. In this survey we show that FTEs serve as an appropriate abstraction for end-to-end network behaviour.

The motivation to investigate the existing technologies on forwarding pipelines which refers to the functionalities of networking elements, forwarding rules and the topologies connect these elements. These functionalities determine the forwarding path of packets which are similar to the pipelines in a watering system, hence also called as *packet forwarding pipelines*.

In this survey, we will review the literature on network forwarding and representation of forwarding pipelines. This survey offers an overview on the state-of-the-art advances in representations of the packet forwarding pipelines that contributes to the understanding of key features of a packet forwarding behaviour. This survey reviews existing and up-to-date technical solutions, identifies their basic characteristics to derive the essential FTE attributes which must be covered by an FTE representation.

The goal of a representation is to better understand and utilise the functionality of FTEs inside SDN. An effective FTE representation must meet the following criteria: (i) it should cover the major attributes of FTE, for example, wildcard, prior-ity and multi-table; (ii) it should be capable of exploiting the various manipulations on FTEs such as validation and facilitating FTE placement; and (iii) it should have the ability to integrate network information such as traffic statistics and topology to resolve realistic networking problems. With the help of the representation, a controller can easily transfer high-level policies to low-level FTEs and correctly place them into switches or routers.

The scope of this survey includes FTE representation and networking applications based on the analysis of different approaches to characterizing FTEs. In the review of a FTE representation, the forwarding pipeline in traditional networking and SDN are inspected and characterised which forms the basis of the taxonomy we develop later in the survey. Moreover, the various representations to analyse FTE (called a typology - grouping of FTE representations with shared similarities) as well as the rationale why they are chosen and their respective applicable scenarios are presented. To better relate the outputs of this survey to practice, we review two types of applications: (i) assessing equivalence in forwarding behaviour and (ii) traffic monitoring.

An overview of SDN is given in Section 2 to guide readers through the concepts, architecture, and the de-facto protocol (OpenFlow) of SDN. It is then followed by the deconstructing the forwarding pipeline in both the traditional network and SDN in Section 3. This is followed by the core contribution of this survey which is a taxonomy of FTE representation in Section 4. Next, the taxonomy is applied to systematically categorise the literature with comments related to why they are suited and their respective application scenarios in Section 5. Finally, a summary of this survey is given in Section 6.

2. SDN: Overview

In a networked system, network elements have two basic components: the control plane and the data plane. The control plane performs control logic such as routing protocols, middlebox configuration while the data plane forwards the traffic based on control logic. The control plane and data plane are coupled together, thus enabling each network element to participate in route making decisions and data forwarding.

However, this tight coupling is not flexible when the network size increases. The obfuscated control

logic coupled with proprietary hardware and the use of low-level programming languages makes the system rigid and complex. Therefore it copes poorly with issues of scalability, reliability and security which are more pronounced as the network size increases. These issues in the traditional network hinder the performance of the system as the network traffic is increasing by the day [7, 8, 9, 10, 11].

To cope with the aforementioned issues in the traditional network, a network paradigm called "Software-Defined Networking" (SDN) was seen as the next generation of computer networking. SDN has two defining characteristics that sets it apart from traditional networks: (a) it separates the control plane from the data plane, and (b) it logically centralises the control plane to direct multiple data plane elements through a single software control program [12]. From SDN, new areas of research such as Network Function Virtualisation (NFV) have emerged, network service chaining, network as code have emerged [13, 14, 15, 16, 17, 18, 19, 20, 21].

A simplified architecture view of an SDN is depicted in Fig. 1. The core of an SDN enabled network is the controller which not only exercises direct control over all networking devices, but also responds to the requests from the application side. A controller communicates with the higher-level components, the applications, via the northbound interface. Similarly, it also communicates with the lower-level components for example the network elements across the network, via the southbound interface.

Some protocols for the southbound interface are OpenFlow [22], ForCES [23], Border Gateway Protocol (BGP) [24], Network Configuration Protocol (NETCONF) [25], Open vSwitch Database Management Protocol (OVSDB) [26, 27], OpFlex [28]. OpenFlow is among the first and most widely used protocol to define communication between the controller and switch in an SDN paradigm [29, 30, 31, 32].

Traditional network management protocols such as NETCONF or routing protocol such as BGP have been reused to configure the switches in SDN. Even though these protocols do not provide the same flexibility as OpenFlow, they are considered as southbound APIs and supported by major vendors such as NEC, Pica8 and HP. Some alternatives to OpenFlow have been documented in the literature for example OVSDB, ForCES
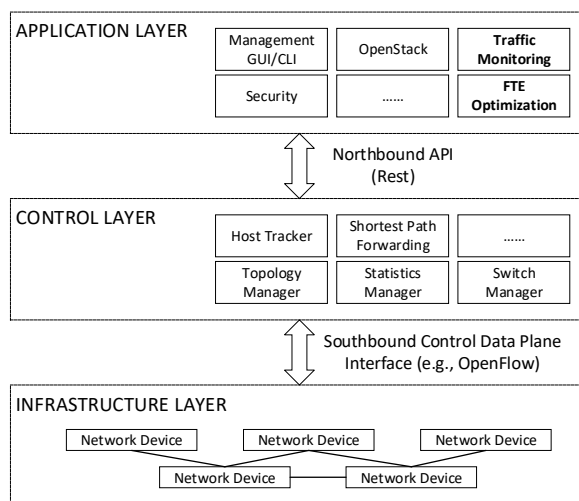

Figure 1: Simplified SDN Architecture

and OpFlex. OVSDB manages Open vSwitch implementation by adopting a non-OpenFlow protocol to program OpenFlow switches. Similar to OpenFlow, both OpFlex and ForCES follow the policy-driven mechanism. OpFlex replaces the OpenFlow controller and OpenFlow interface with "Policy Authority" and "Policy Agent", respectively. However, the switch in OpFlex still relies on the FTE-like flow tables to forward packets.

As a competing protocol with OpenFlow, ForCES is different from OpenFlow in many aspects, but they share the same design principle in forwarding models. ForCES manages the packet forwarding behaviour with an abstraction of Logical Functional Blocks (LFBs) which share the similar functionality as OpenFlow FTE. Both LFBs and OpenFlow tables consist of "Match-Action"-like entries, i.e. FTE. Therefore, the underlying principles of an SDN forwarding discussed in this survey extends to non-OpenFlow protocols too.

Recent surveys have shown that the proliferation of SDN across different domains is widespread [33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44] even reaching emerging areas such as machine learning [43, 42, 45], Internet of Things (IoT) [46, 47, 48] and blockchains [49, 50]. Our extensive research of the literature has identified that none of the surveys in the recent two years have collated and studied FTE representations and classified them as we have done in this survey.

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3. Forwarding Pipeline

In networking, a pipeline is a chain of packet-processing entities (or filters) connected in a certain type of structure, where the output of one entity is the input of another one. For an individual networking device (switch or router), the packet-processing entities include the various chained forwarding tables such as the ACL table, IP routing table in traditional networking and generic forwarding table in SDN. Similarly, for a network (traditional or SDN), the packet-processing entities include forwarding tables in all networking devices which are connected with a certain type of topology. This pipeline is also called *packet forwarding pipeline* because its major function is forwarding data packets between two devices.

3.1. Forwarding tables in traditional networking and SDN

As illustrated in Fig. 2, a packet's forwarding path is determined by the forwarding tables in each network element. The forwarding tables in traditional networking are usually statically configured or generated by locally running routing protocols. Whereas, the forwarding tables in SDN can be dynamically provisioned and updated by a centralised controller.
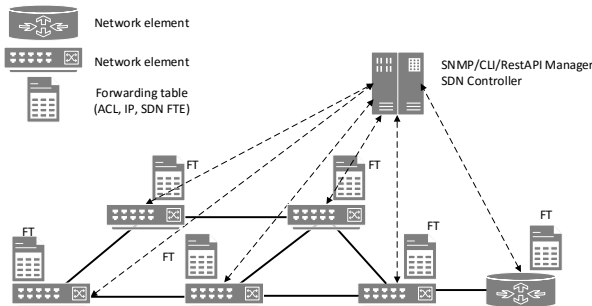

Figure 2: A network abstraction: forwarding tables

Traditional networking mainly relies on routing and switching protocols such as BGP (Border Gateway Protocol), IGRP (Interior Gateway Protocol) and Ethernet to perform packet forwarding. However, some applications such as firewall and load balancing need more flexible ways to dynamically regulate the network. To meet this requirement, the concept of an ACL was introduced by Cisco to provide an alternative to manipulate the switch forwarding behaviour. An ACL can be considered as a special purpose filter in a forwarding pipeline which is designed to specify the access rights allowed or denied for all incoming packets.

Besides an ACL table, an IP routing table has also been widely used in a forwarding pipeline [51]. In a network, each networking device maintains a routing table which consists of a set of IP prefix entries and their associated egress interface(s). When an IP data packet reaches a device, this packet's destination address will be matched against the routing table to find its egress interface(s) by matching against the longest IP prefix. Compared to an ACL, an IP routing table is a generic purpose filter and the most important components of a forwarding pipeline. IP routing tables determine a packet's forwarding path in a network.

From the above two functions, we can see that ACL policy and IP routing in tandem with the underlying protocols perform the following two steps to achieve "network management": (i) the incoming packets match against ACLs or IP route (e.g. prefix matching) and (ii) execute certain actions (drop or output packets). This specific design for each ACL and IP routing function is radically changed by use of forwarding tables in SDN [52].

The core concept of an SDN is that by creating a few careful abstractions based on ACL and IP routing tables, the complexity of the underlying components is hidden and the new functionalities are easily developed via the programming interface between the network devices and the controller. One popular programming interface is OpenFlow which is the de-facto southbound interface that gives the higher level software access to the forwarding plane of an SDN. In OpenFlow, FTE has replaced the ACL and routing entry of traditional networking to manage the forwarding capabilities of networking devices. Packets are forwarded according to the path which is composed of FTEs. For a pure SDN, the behaviours of all packets can be precisely controlled by manipulating FTEs.

OpenFlow was proposed around 2008 and it is still evolving as the mechanism and usage of FTE are not fully researched [53]. The core idea of FTE is similar to the policies which have been widely used in an ACL while the policy's scope and depth have been largely extended in OpenFlow. As the network scales and grows in complexity, FTEs are not easy to understand and manipulate. Therefore, it is important to find a way to represent FTEs as

they determine the packet forwarding behaviour in an SDN.

The two major perspectives of OpenFlow specification are FTE manipulations (installation, deletion, modification) and statistics updates [54].These perspectives motivate the research on FTE representation and manipulation for better management of an SDN. In the following subsection, existing research works on characterising forwarding behaviour are discussed. The significance of FTEs and how they relate to optimal network utilization has been discussed in the works of [55, 56] whereby the relationship between flow table occupancy and link utilization is established.

3.2. Existing works on characterising forwarding behaviour

Existing works that investigate the forwarding behaviour of packets can be classified into three categories based on three different forwarding tables whose structures and functionalities vary. The three forwarding tables are i) ACL, ii) IP routing entry, and iii) FTE. This subsection reviews the existing works for all these three forwarding tables and derives the four essential attributes for a successful forwarding pipeline representation.

3.2.1. Regulating forwarding behaviour by ACL

An ACL is composed of a sequence of rules to match against the packet to determine whether a specific action is performed or not. It is a special type of role-based access control (RBAC) [57]. A "minimal RBAC Model" (RBACm) can be compared with an ACL mechanism (ACLg) where only groups are permitted as entries in the ACL [58]. An ACL has been widely used in a computer system such as the user account authentication, firewall, etc. The prior research on ACL is mainly focused on the validation of these access control policies and the optimization of their storage space.

Lampson introduced the formal notions of *subject* and *object* as well as an access matrix that mediated the access of subjects to objects [59]. An *access matrix* consists of a set of subjects $s \in S$, a set of objects $o \in O$, a set of operations $op \in OP$, and a function $ops(s,o) \subseteq OP$, which determines the operations that subject s can perform on object o.

To model a simple network as an access matrix, we use an example of a network enforcing an

ACL. Fig. 3 shows an ACL example where a select host in NetB is granted permission to access NetA. All traffic from Host B destined to NetA is permitted while all other from NetB destined to NetA is denied. Its corresponding access matrix is demonstrated in Table 1. The specified operations (permit host 192.168.10.1) are performed on all incoming packets which are the implicit objects of an access matrix.
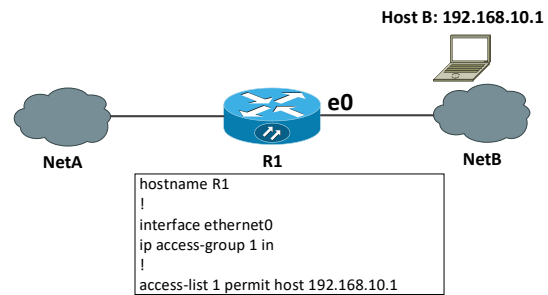

Figure 3: An ACL example with corresponding access matrix

Table 1: Access matrix for the ACL example in Fig. 3. The access matrix resides in router R1.

Subject	Object	Operation
Interface ethernet0 (e0)	Incoming packets	Permit host 192.168.10.1
*	*	Deny

An access matrix can be easily transformed to the "match-action" form (MAF) which has been specified in OpenFlow specification [60]. For an example in Fig. 3, its equivalent MAF is illustrated in Table 2. An MAF does not include the field of object in access matrix because all ACLs share the same object: incoming packets. The action in MAF only contains two operations: permit and deny.

The default action for all packets which are not explicitly permitted by ACLs is denied which is why the second row is added in Table 2. The match field in a MAF is composed of an access matrix's subject and the negatives of the fields in operation. From the perspective of functionality, an ACL is equal to a generic forwarding table with no constraints on match fields and only two type of actions (permit and deny) allowed.

3.2.2. Regulating forwarding behaviour by IP Routing Table

An IP routing table determines which specific route is selected for a given IP address. The table

Algorithm 1 Routing table semantics

1: **datatype** (′a,′b) linord-helper = LinordHelper ′a ′b
2: **begin**
3:     **definition** *linord-helper-less-eq1 a b ≡ [case a of LinordHelper a1 a2 ⇒ case b of LinordHelper b1 b2 ⇒ (a1 < b1) ∨ ((a1 = b1) ∧ (a2 ≤ b2))]*
4:     **definition** *a ≤ b ⟷ linord-helper-less-eq1 a b*
5:     **definition** *(a ≠ b ∧ linord-helper-less-eq1 a b)*
6: **end**
7: **theory** *Routing-Table*
8: **import** *../IP-Address/Prefix-Match*
9:     *../IP-Addresses/IPv4 ../IP-Addresses/IPv6*
10:     *Linorder-Helper*
11:     *../IP-Address/IP-Address-toString*
12: **begin**
13:     **record(overloaded)** *′i routing-rule =*
14:         *routing-match :: (′i::len) prefix-match*
15:         *metric :: nat*
16:         *routing-action :: ′i routing-action*
17:     **record(overloaded)** *′i routing-action =*
18:         *output-iface :: string*
19:         *next-hop :: ′i word optio*
20: **end**

Table 2: "Match-action" form for the ACL example in Fig. 3

Match Fields	Action
Ingress port = Ethernet 0 Destination IP Address = 192.168.10.1	PERMIT
*	DENY

entry in an IP routing table represents the smallest subnet that contains the given IP address. A routing table captures two aspects: Composition and Relation [61]. The Composition aspect deals with the components of a routing table and their respective meaning while Relation interprets a routing table from different functional perspective. The structure of an IP routing table with the Composition and Relation aspects is illustrated in Fig. 4.
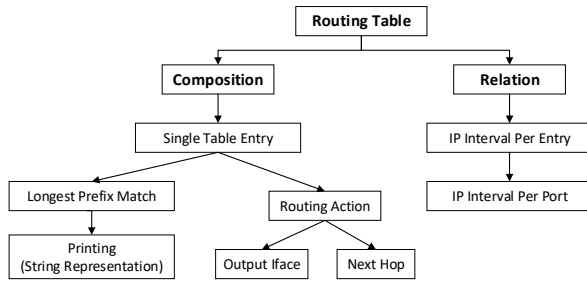

Figure 4: IP routing table structure

As seen in Fig. 4, a routing table is composed of single table entries where each entry contains a longest prefix IP address and its corresponding routing action (a subset relationship). The relation between an IP address and its corresponding routing action can be then interpreted from the two functional perspectives: 1) IP interval per entry and 2) IP interval per port. The IP interval per entry is a function from IP (interval) to port (where the intervals do not overlap) while the IP interval per port is a function from port to IP (a range of IP addresses or an IP space). Algorithm 1 defines the routing table semantics [61] in which the datatype *linord-helper* maps the set relationship between two IP addresses (lines 2-6). It is used to express the concept of longest prefix match (LPM) (lines 13-16). For all IP packets which match the given routing table entries (lines 8-11), they will be forwarded to the corresponding output interface or next-hop depending on their associated routing-actions (lines 17-19).

3.2.3. Regulating forwarding behaviour by FTE

OpenFlow provides an industry-standard application programming interface and protocol to program forwarding tables in switches. OpenFlow is managed by Open Networking Foundation (ONF), an organization dedicated to promoting and adoption of SDN. OpenFlow is evolving and will continue to evolve. The latest OpenFlow switch specification is Version 1.5.0 (Protocol version 0x06) [60] which was released on December 19, 2014 by ONF.

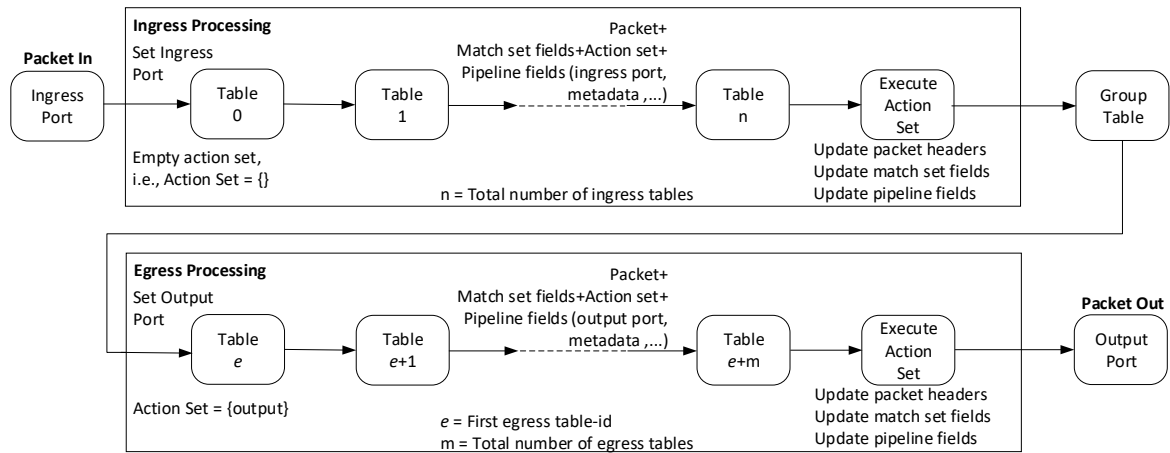Since OpenFlow Version 1.1.0 [62], a flexible
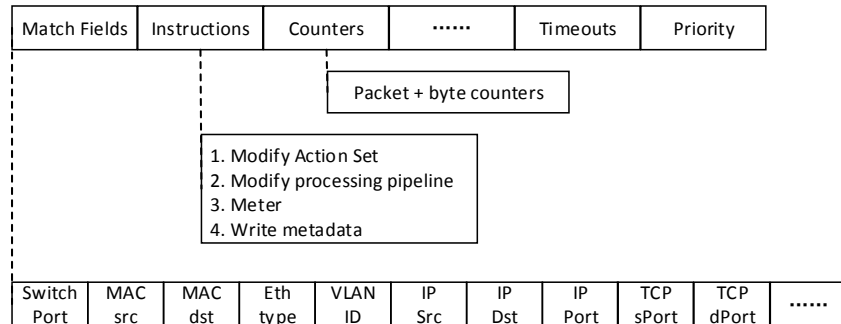
Figure 5: OpenFlow table processing [60]

Figure 6: Inside FTE: OpenFlow packet matching and actions

pipeline with multiple tables is exposed to the control layer. As depicted in Fig. 5, packets are processed through a pipeline which consists of one or more flow tables, group tables whereby each table consists of multiple FTEs. The pipeline has two processing stages: ingress processing and egress processing which is separated by the first egress table as seen in the Fig. 5 [60]. The pipeline processing starts with ingress processing from the first flow table, labeled "Table 0" in Fig. 5. The output of ingress processing may direct a packet to an output port in egress processing which is optional. The incoming packet "Packet In" must be matched against FTEs of "Table 0" and subsequently the packet might be forwarded to any table following "Table 0" based on the action set and pipeline instructions such as metadata which carries information between tables. When a packet is matched against the FTEs of a flow table, a matched flow entry is selected to execute a set of instructions.

The instructions can be to forward the packet to a specific port or another table. The instructions can also direct the packet to a Group table for further processing as seen in Fig. 5. The group table is used to execute group actions on packets and consists of group entries. A Group table contains forwarding entries and actions for packets associated with a group, which can be a set of TCP ports, or a set of actions applied to traffic aggregates. The Group table functionality represents an area that is under studied within the SDN context but can be extremely powerful and flexible. Finally, if a packet has no matching flow entry in a flow table, the packet is processed depending on the instructions specified in the table-miss entry.

The match fields and actions in FTE can be easily customised to implement the same forwarding behaviour as ACL and IP routing entry [63]. For an ACL, the match fields remain the same as FTE,

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only the ACL's default action "deny" is replaced by "drop". The conversion from an IP routing entry to an FTE is more straightforward, neither the match fields or actions need any changes. But not all match fields in traditional networking are explicitly indicated. For example, the packets with specified VLAN id and destination MAC (DMAC) address will be only sent to an IP routing table for prefix searching. Therefore to maintain the same forwarding behaviour as an existing IP routing entry, the match fields of FTE will become the combination of "VLAN, DMAC".

A flow table consists of multiple FTEs. Fig. 6 illustrates the main components of an FTE: match fields, instructions, counters, timeouts and priority. An FTE is identified by match fields and priority. The match fields determine whether a packet can hit an FTE while the priority determines whether a packet has the chance to match against this FTE or not. Only the matching FTE with the highest priority will be selected. A match field contains the well-known fields in an IP header (source MAC, destination MAC, source IP, destination IP, etc.) as well as the fields related to pipeline processing, for example, ingress port and metadata.

From the research works [64, 65, 66] on SDN forwarding table, there are four essential FTE attributes: i) Wildcard [W], ii) Priority [P], iii) Multi-table [M], iv) Topology [T]. The attributes can be extended by taking into consideration whether an FTE supports group actions or not, however this is beyond the scope of this survey because it is a feature that hasn't been widely studied at the time this research was conducted.
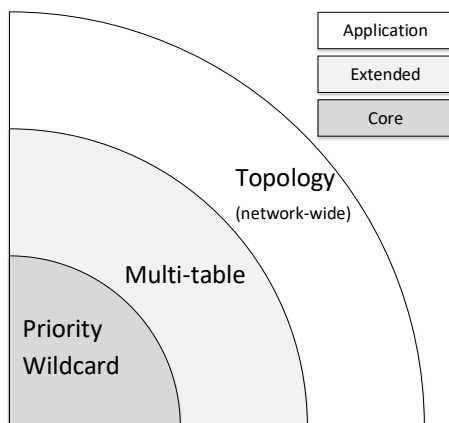

Figure 7: OpenFlow attributes

Among the above key attributes, wildcard and priority are only associated with a single table. Wildcard and priority are inherited from an ACL and a lot of research has been done on these attributes [67, 68]. As illustrated in Fig. 7, they are categorised as core attributes and must be covered by all representations. Multi-table is one of the most significant feature in OpenFlow to enrich dynamic configuration and placement of a FTE. Multi-table is listed as extended attributes in Fig. 7 and it must be represented by any network-wide representation. Although topology is not an intrinsic attribute of a FTE, it is still listed here as a crucial attribute because it plays an important role in determining a network-wide packet forwarding behaviour.

3.3. Pipelines: a common denominator for packet forwarding

Inside a single forwarding element (switch or router), there might have multiple forwarding tables where each table serves a different purpose to match their respective specified field(s) against the incoming packets. These tables construct a packet forwarding pipeline which is the common denominator for ACL and IP routing table in traditional networking as well as the generic forwarding tables in SDN. In the next few paragraphs we will compare by way of example the tables in traditional networking and SDN to highlight the difference in the forwarding pipeline.

The first example is an IP routing table. It has only one match field i.e., the destination IP address to match upon the incoming packets, it is also called a single dimensional forwarding pipeline [69]. The second example is an ACL, which is a multiple dimensional pipeline because it matches against more than one known field simultaneously. However, as the name ACL suggests, it can only decide whether a packet is allowed to pass through a device by its predetermined action: permit or deny.

The SDN paradigm uses a more generic forwarding pipeline which allows arbitrary combination of multiple fields and performs more complex actions. Each of the tables are dynamically provisioned based on the program running in the controller.

In Table 3 we compare the traditional network with SDN. Each table (denoted in the row) is marked with an "x" if the table supports a "Dimension" for matching and is able to perform a set of "Actions". The Dimension column indicates

that the table for the use case is single dimensional (e.g. IP or VLAN or TCP) or multidimensional (e.g. TCP and MPLS). For example, IP routing only requires the source and destination address fields from the IP headers (i.e. one dimension) while ACLs must have the capability for regulating access via both IP headers, TCP headers and potentially other headers (i.e. multiple dimensions).

For ACLs, there are many possible combinations of IP addresses or ports the administrator may want to configure. Hence, multiple dimensions are a must for ACL. The Actions are described below:

- copy: copy TTL (Time-to-live) to/from the packet

- pop/push: apply all tag pop/push actions to the packet (e.g. MPLS or VLAN tags)

- set: apply all set-field actions to the packet

- out: forward the packet on the port specified by the output action

Table 3 highlights a stark difference between different table types in traditional network vs. SDN. From the perspective of matching "Dimensions", the IP routing table only has one dimension which is the IP prefix while the rest two types have arbitrary combinations of the fields in a packet header. From the perspective of "actions", the IP routing table always directs to the next-hop via an "Out" action and associates with a single egress interface. For SDN, the tables can implement an arbitrary combination of actions via the FTE, hence all actions are marked "x".
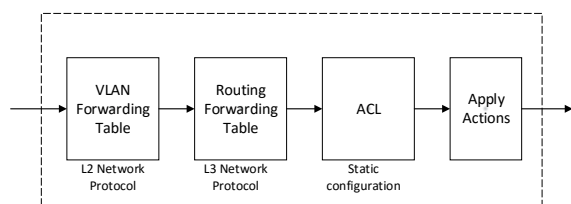

Figure 8: Switch-level pipeline in a traditional network

In traditional networking, each table has fixed width and is assigned the corresponding predetermined functionality, for example, VLAN validation in the first table, IP address prefix matching in the second table and ACL filtering in the third table. However, in SDN, these tables can
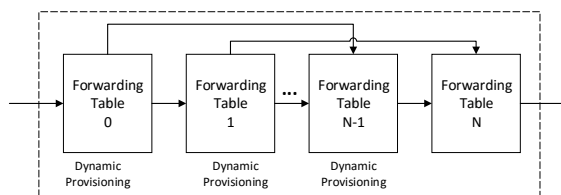

Figure 9: Switch-level pipeline in SDN

be customised and are not restricted to the predetermined actions. Hence, the ACL and IP routing tables can also be considered as a special type of forwarding pipelines. A forwarding pipeline is composed of one or multiple forwarding tables which contain FTEs to specify the match fields and their associated actions.

Though the structure and functionalities of forwarding pipelines have changed significantly from traditional networking to SDN, the underlying hardware remains the same. Most SDN switches on the market share the same hardware as before. Fig. 8 and Fig. 9 illustrate the reference forwarding pipeline of a typical ASIC (application–specific integrated circuit) based switch in traditional networking and SDN, respectively.

4. FTE Representation

Even though the OpenFlow protocol is evolving, various approaches have been proposed to analyse and manipulate the FTE in OpenFlow. A summary of the literature of FTE representation is presented in Table 4. FTE representations have been studied using simple logical connectives [89, 84, 103, 27] to more complex and abstract representations such as infinitary logic.

In general, FTE representations are built upon one or a combination of logic. The term "logic" in this survey is an expression system with well defined syntax, semantics and pragmatics. Examples of single-logic based representations include algebra [77, 91, 90], set theory [87, 78], first-order logic based model checking [98], temporal logic [71, 74, 75], and higher-order type theory [95, 96]. Single logic for FTE representations cannot completely capture the complete attributes for OpenFlow such as the Topology and dynamic table placements. However, single-logic representations are much more tractable and have been the most popular in the literature.

Table 3: Forwarding table comparison

Network	Table	Dimensions		Actions			
		Single	Multiple	Copy	Pop/Push	Set	Out
Traditional Network	ACL		x			x	x
	IP routing	x					x
SDN	FTE	x	x	x	x	x	x

Some representations that adopt more than one logic which includes Z [91, 90] and multiple-logics based model checking [73]. The Z representation is developed from typed first-order predicate logic and Zermelo-Fraenkel set theory. Multi-logic representations of FTE in SDN are not as well developed compared to single-logic, examples of research applying multi-logic are [86, 104, 105].

Our proposed FTE representation is divided into four main typologies (Table 4) namely: logical connectives (LC), algebra (AL), set theory (ST) and formal representations (FR) and each representation has been shown to be able to model one or more OpenFlow attributes described earlier in Section 3.2.3. In this survey, a typology is defined as a grouping of FTE representations with shared similarities. Collectively, the typology and the ability to model out the OpenFlow attributes define the taxonomy of FTE representations in the literature.

4.1. Logical connective (LC)

This typology is denoted as LC in Table 4. *Logical connective* representation mainly utilises logical operators to express the relation and interactions between FTEs. The relations that can be in place among match fields and instruction sets are first analysed in [89]. Based on potential relation combinations, the five FTE interaction types: *Disjoint*, *Exact match*, *Subset*, *Superset*, and *Correlated* are defined in [89].

4.2. Algebra (AL)

Algebraic typology is denoted as AL in Table 4. *Algebraic* representation is good at describing the attributes and reasoning of a structure or program. The simplest algebra is *Boolean algebra* [106] in which the values of the variables are the truth values, *true(1)* and *false(0)*. Another branch of well-studied algebra representation pioneered by E.F. Codd called relational algebra [107], was proposed to model the data stored in relational databases.

Kleene algebra [108], partly built on relational algebra focuses on the semantics of a program which can be expressed as an idempotent semiring. NetKAT [76, 77] is another network programming language which is build on top of Kleene algebra has demonstrated its capability of representation for the attributes such as priority and topology. However, there is no evidence to show that NetKAT can also be used to represent multi-table in SDN. A recent paper by Skalka et al. [86] relates to the concept of algebras to networking in practice and is significant in demonstrating practical application of algebra in SDN.

4.3. Set theory (ST)

Set theory typology is denoted as ST in Table 4. *Set theory* (Frenetic [87]) is concerned with the concept of sets. It studies the well-determined collections of objects. However, its strength lies in descriptiveness rather than manipulation, thus it is unlikely to fulfil the desired functionalities related to FTE manipulation, for example, removing the priority in a single table and combining multiple tables.

4.4. Formal representations (FR)

Formal representations is a large family of representations with a long history that predates SDN. Formal representations use rigorous and provable mathematics in the design and implementation of the FTEs. It is a process to derive logical conclusions from the premises which are true or assumed to be true. A formal representation for forwarding pipelines opens up new opportunities for applying formal methods to the analysis, design and optimization of SDN. Formal representations can be categorised based on the underlying logic used and for representing FTEs these are: (i) symbolic logic and (ii) mathematical logic.

4.4.1. Symbolic logic

Symbolic logic uses symbols and variables to express logical ideas. It is by far the simplest kind of

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Table 4: Summary of FTE manipulation

Topology	Logic	Modelled Attributes[*]	Applications	Project and Reference
FR	Binary decision diagrams, Computational Tree Logic	[WP]	Identify misconfiguration	RuleChecker [70], FlowChecker [71]
	Rule partition	[WPT]	Scalability	SGLS [21],DIFANE[72],[20]
	Propositional logic, temporal logic	[WPT]	Test and verification of OpenFlow applications	FlowLogic [19], GVCM [18], NICE [73]
	Computation Tree Logic	[T]	Slicing and Isolation	Slicing abstraction [74]
	Linear temporal logic	[P]	Action-based synthesis of SDN	Automated Synthesis of Controller [75]
	Coalgebraic theory, Kleene algebra, Brzozowski derivative	[PT]	All-pair connectivity, Loop-freedom, Translation validation	NetKAT [76, 77]
ST	Declarative language, Domain specific languages, Set-theoretic operations	[WPT]	A compiler, transformation from application-level policies to switch-level policies transformer	FastRule [17],NetCore [78]
	Rectangular representation and selection	[WPT]	Rule placement (space, time, resource)	Mozart [15],"One Big Switch" [79]
	Brick based model	[WP]	OpenFlow Failure-planning	Semantic [11], RuleBricks [80]
	Tree decision model, partition	[WP]	Flow setup efficiency improvement	CAB [81]
	Integer linear programming mode	[T]	Maximise traffic satisfaction	Routing for Efficiency [82]
	Graph-based model	[PT]	Energy-aware Routing	EAR [83]
	Graph theory, Recursive theory	[WP]	Caching system for SDN, FTE abstraction	CacheFlow [84]
	Tree-based model, Tagging approach	[PM]	FTE compression	Generalised FTE Optimisation [85]
LC	Set theory	[WPT]	Application oriented network programming language over controller	PCNC [86],Frenetic [87]
	Logic connective	[WP]	Generic analysis, management and optimization of FTE	OpenFlow rules interaction [65, 88, 89]
AL	Algebra of communicating shared resources	[P]	Formalisation and verification of SDN framework	Formal Specifications [90, 91, 92, 45]
	Tree based model, partition	[WPT]	Traffic-optimal rule placement	BigMAC [13],vCRIB [93]
FR, AL	Tree composition/decomposition	[M]	Multi-table processing on legacy hardware	Equivalence [16], FlowAdapter [94]
	Domain-specific languages	[WPT]	SDN controller verification	Featherweight OpenFlow [95, 96],Coq [97]
	First order logic, Logical connective	[WP]	Verification of security attributes in OpenFlow	MSAID [14], FLOVER [98]
ST, AL	Rule Decomposition, Graph-based model	[PT]	Rule decomposition, distribution and placement	Palette [99]
LC, FR	CAP (consistency, Availability, Partition) theorem [100]	[WT]	Trade-off between policy enforcement and network connectivity	CAP for Networks [101]
ST, FR	Algorithmic Policies	[WPT]	Simplify SDN Programming	Maple [102]

[*] Modelled attributes: W - Wildcard; P - Priority; M - Multi-table; T - Topology

logic. Variants of symbolic logic includes **propositional logic** [109], **predicate logic** [110] and **temporal logic** [111]. Among these three logics, propositional logic has no quantifiers while the other two have. The quantifiers are quite useful to express the uncertainties in a forwarding pipeline, such as load balancing and failover [73] in which the same packet might be forwarded to different paths.

Propositional logic studies the indivisible statements. It assumes every statement can be interpreted as true or false and then produces more complex statements in which truth-value depends on the truth-values of the simpler statements. The symbols or words used to connect two statements are logical connectives which include binary connectives such as *"or"*, *"and"* as well as unary connectives such as *"negation"*. It has been proven useful in modelling network forwarding pipelines where each entry is interpreted as a logical expression of the conditions to trigger their associated actions [109].

Since propositional logic is not able to represent the relationship between propositions, a more powerful logic "predicate logic" has been studied in [110]. Predicate logic is an extension of propositional logic and more expressive. It uses quantified variables such as existential "∃" ("there exists") and universal "∀" ("for all") over objects to define the scope of the statements. Predicate logic is a generic term of **higher-order logic**.

These logics can describe functional relationships and statements about "for all" objects or about "for some" objects but their quantifiers vary. First-order logic quantifies over individuals of the domain of discourse. Higher-order logic is distinguished from first-order logic by additional quantifiers. As illustrated in Fig. 10, higher-order logic quantifies over sets or sets of sets while first-order logic has the quantifiers of non-nested sets.

Modal logic extends the classical proposition logic and predicate logic to allow the quantifiers to express modality, for example, "necessarily" and "possibly" [111].

Compared to logical connectives and Boolean algebra, the aforementioned logics in Fig. 10 are high-level abstraction which indicates that they are better at expressing the connections among FTEs, for example, the priority and topology. However, the low-level FTE attributes such as wildcard and "goto table" actions are easily overlooked by these logics.
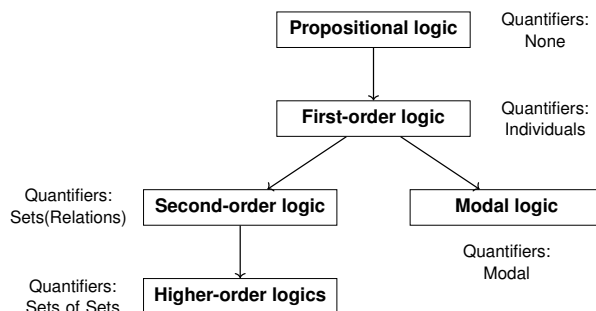

Figure 10: Quantifiers of logic

4.4.2. Mathematical logic

In mathematical logic, Boolean algebra is a branch of algebra in which the values of the variables are the truth values "true" and "false", usually denoted by 1 and 0, respectively. Boolean algebra is naturally suitable to represent SDN forwarding pipeline especially on the applications such as the equivalent forwarding set evaluation and traffic monitoring. In the former scenario, the question turns to the Boolean function on the match fields for the same action. In the latter scenario, the question turns to find all supersets/subsets and retrieve their individual statistics for a given flowset.

To fit the Boolean algebra to a FTE, two challenges must be addressed: wildcard logical operations and deprioritisation. In traditional networking, wildcard algebra is only supported on lower bits (at the rear) of an IP address or MAC address to facilitate the longest prefix search, it may locate at any position in a FTE. Thus the Boolean algebra on FTE must allow the wildcard be positioned anywhere and accepted by all Boolean operations.

In this survey, "wildcard" stands for "wildcard mask" which was first coined by Cisco. It is a mask of bits that indicates which parts of IP addresses are available for examination. For example, a wildcard mask 0.0.0.3 represents that the last two bits are not available for examination. A packet with an IP address which ends with bit 0 or 1 will have the same examining result. A wildcard mask is continuous and always indicates the last certain number of bits are not available for examination. Thus a wildcard mask in a truth table has the following format: 1000011111****, 000111**, 110000* in which the number of asterisk is flexible while they always position at the rear of a Booelan value. However, in FTE, a more flexible

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format of wildcard is expected in a truth table, the wildcard (*) should be positioned anywhere (not only in the rear of a value), such as 10000**111****, 10000**0011, ***111000.

Another challenge is introduced by a FTE's unique attribute: "priority". Due to the prioritisation within a forwarding table, most FTEs' match fields cannot reveal their actual matching scope. After appropriate adaptations and extensions, Boolean algebra extends the existing SDN application into multiple flow tables across multiple switches.

Besides the intrinsic FTE attributes, wildcard and priority, Boolean algebra is also capable of representing another two attributes: multi-table and topology. The Boolean operations (for example, logical AND (∧) and OR (∨)) between any two forwarding tables or even two switches can be converted to the operations between the FTEs in their respective tables or switches.

Besides Boolean algebra, other mathematical logical methods have also been examined to investigate the possibility of representing FTE and exploiting their applications. It is found that propositional logic and some lower-order logic are also good at expressing SDN forwarding pipeline. However, the abstraction in the process of FTE representation makes these approaches less applicable in practical scenarios where some low-level information is already lost. For example, the relative positions of multiple forwarding table entries and the connections among multiple tables are hard to be represented in these logics.

Among all the formal semantics, NetKAT represents single table very well and maintains most essential low-level information. However, the challenges on Boolean algebra exist for NetKAT as well, which means the similar adaptations and extensions on Boolean algebra are also required for NetKAT. Moreover, its initial design does not cover the multi-table attribute which further limits its applicable scope. For low-level representation, Boolean algebra is unlikely to reveal the whole picture of network-wide forwarding pipeline. However, it can be easily extended to support the latest SDN core forwarding attributes such as priority and multi-table.

Some research in Table 4 adopts the data structure based representation such as brick, tree and graph [72, 94, 79, 99, 93, 101, 81, 83, 85, 112]. They are not discussed in this survey because they usually aim to resolve a specific problem rather than providing a generic solution. For example, the RuleBricks [80] provides high availability (HA) policies to OpenFlow forwarding pipeline. This survey intends to find a representation which is not particular to any application.

5. FTE representation in practice

Based on the analysis of FTE, various applications have been developed. These applications can be mainly categorised into two types from functionality perspective: FTE placement and Traffic monitoring. FTE placement mainly covers the following aspects: i) FTE manipulation [113, 114, 94, 115], ii) consistent updates over multiple switches [116, 117, 118, 119, 120], and iii) placement optimisation [121]. All these three placement applications rely on the correct conversion among the different forms of tables across multiple switches. The works on traffic monitoring include traffic estimation [122], traffic anomaly detection [123], verification of forwarding tables [88], etc.

5.1. Optimising FTE

Prior works on FTE's placement optimisation can be further divided into two categories: single switch flow table optimisation [80, 81, 124, 125, 126, 127] and network-wide flow table optimisation [83, 79, 99, 85, 93, 82, 101, 102, 72, 55].

The optimisation of single table usually focuses on compression which heavily relies on the mechanism "merge" and " split". The new installed rules are firstly merged with each other and then split according to the structure and size a hardware forwarding table. Then the neighbouring or function-alike flow entries can be further merged to save table space.

Another optimisation approach is to deploy FTEs according to their different access frequencies, for example, deploying the most frequently accessed FTE in a high-speed cache and the relatively unpopular FTEs in a low-speed cache [124]. In the scenario of FTE compression, a number of practical advances to increase the applicability of a hardware resilience via forwarding table compression algorithm and compression-aware routing have been discussed [128]. A method to verify whether redundant rules exist and to avoid them during incremental deployment are also proposed and verified [127].

A major drawback of this "merge" and " split" approach is that it fails to explore FTE's multi-table

capability. Some researchers notice the benefit of multiple flow tables and they perform partitioning and compression by distributing forwarding rules into different tables according to their respective capabilities [125]. Network-wide optimisation is usually achieved by "combination" and "distribution". In a given interval, all requests from different applications will be combined as a single composite request and then reorganises and distributes the FTEs to the devices. During this process, the exact path specified by the original application might be changed. It enriches the freedom to adjust the FTE placement across all applications, however, the achievements of some higher-level goals such as traffic engineering cannot be guaranteed.

A core question for any deployment of multi-table FTE is related to assesing the equivalence between the table(s) to be provisioned and the table(s) deployed in the switches. Particular attention about multi-table evaluation and deployment should be paid to the research in [129] and [94, 45]. The former proposed a reconfigurable match tables (RMT) model which allows the forwarding plane to be modified by reorganizing the tables (for example, adding new match fields and reconfiguring IP lookup tables) [129]. The latter proposed a middle layer to convert flow rules (FTEs) from the controller to a flow table pipeline of a hardware switch. In a hardware switch, the transformation from one single policy to a multi-table rule is usually required so that the rules can be fitted into different types of hardware [94]. Both works in [129] and [94, 56] are concerned with the conversion between different types of forwarding tables.

However, it is found that the OTN (the conversion of a One-stage flow table into *N*-stage flow tables) proposed in [94] is not always correct. Its core idea is to fill the corresponding match field value of a one-stage flow entry to multi-stage entries based on their containing match field types, as illustrated in Fig. 11.

In this conversion, the original single table (Table 1) has been converted into a multi-table structure (Table 2 and Table 3). Take the first entry in Table 1 as an example, the original match fields {A, B} are decomposed and distributed into {A} in Table 2 and {B} in Table 3, respectively.

Closer analysis of the FTEs reveals that packets matching either {A, B} or {C, D} will behave the same while the packets with {A, D} or {C, B}

will not. The packets with attributes {A, D} will NOT match any entries in the single table and will be dropped by default. However, in the converted multi-table, the same packets can match the first entry in Table 2 and then the second entry in Table 3 sequentially which means the matching packets will egress out of port 2. For the same packets, the forwarding behaviour will not be the same which means the single table is not equivalent to the multi-table. Thus, a systematic approach to evaluate the equivalence of any two given forwarding sets becomes a challenge for all forwarding table manipulations.

5.2. Traffic monitoring

FTEs can be used as a modelling tool to design network monitoring solutions, e.g. placing FTEs across a certain end-to-end path. The most widely adopted network traffic monitoring approaches are either based on packet sampling or sketch-based measurements. Sampling-based monitoring solutions are dominated by NetFlow [130] and sFlow [131]. NetFlow is a feature on Cisco routers for collecting IP network traffic with pre-determined rules. sFlow, short for "sampled flow" provides a means for collecting information of truncated packets together with the interface statistics. Since the set of FTEs in an SDN controller is like a "traffic map", the packet statistics related to a flow across a network can be interrogated and used as an estimation for traffic monitoring purposes [132, 133].

Traffic monitoring with sFlow offers greater scalability (compared to NetFlow) and it reports information on network traffic (corresponding to OSI (Open Systems Interconnection) layer two to layer seven) in detail, but it consumes more resources (e.g., CPU, memory, and bandwidth) [134, 92]. A high sampling rate generates too much information (costly to store), while a lower sampling rate may result in heavy-hitter flows going undetected.

Compared to a sampling-based monitoring, a sketch-based approach can process millions of streams in a short time with low overheads. A sketch-based approach is a probabilistic summary of data streams within a compact data structure that builds forecast models on top of sketches which represent the past traffic patterns. A Sketch-based approach adopts an unique hash function and associates multi-dimensional tables to data

Match	Action	Priority
A, B	Output 1	2
C, D	Output 2	1

Single Table

?

Multiple Table

Match	Action	Priority
A	Goto Table 1	2
C	Goto Table 1	1

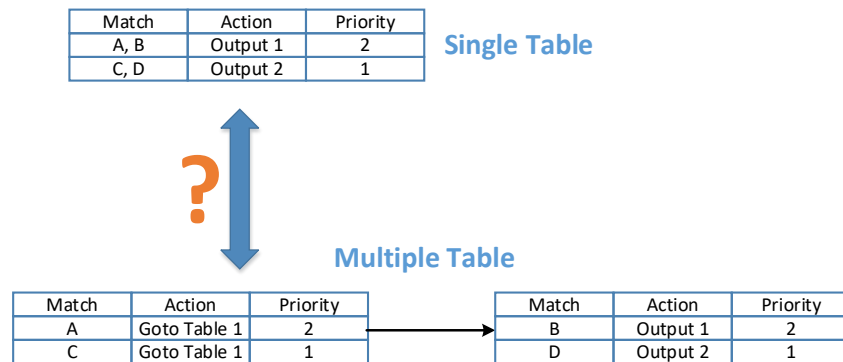| Match	Action	Priority
B	Output 1	2
D	Output 2	1

Figure 11: Match fields distribution of OTN conversion

streams for storing summarised data which requires customisation of existing switch ASIC. This is why most of the existing works are only verified by simulation and implemented on field-programmable gate array (FPGA) [135, 136].

To fit the aforementioned approaches into the realistic network monitoring scenario, ProgME (Programmable Network MEasurement) presents a framework to measure a flowset defined according to an application requirement [137]. A statistics query is processed by a query answering engine which maps a flowset to unique flows whose statistics can be retrieved directly from a hardware. Even though the scenarios of these traffic monitoring research vary, they share the same principle, i.e., to measure an arbitrary set of flows' traffic based on the ready statistics.

No matter what kind of approaches and frameworks are chosen, all the existing SDN traffic monitoring solutions use the same way to get the statistics. They install the application specified rules and then retrieve their statistics [138, 139, 136, 140, 141]. The benefit is that the controller can customise the FTE rules for flexible traffic monitoring, for example, the controller is able to update the FTE rules to monitor suspected malicious traffic dynamically. However, it is difficult to avoid the interference on the active traffic because the behaviour of all the packets matching these monitoring FTEs will be altered.

6. Conclusion

This paper reviews the recent literature on the representation and application of packet forwarding pipeline. Software Defined Networking (SDN) enables a network to be intelligently and centrally controlled via forwarding table entries. The structure and functionality of FTE are more complicated than the traditional networking functions such as ACL and IP routing because of its generalisation. We propose a new taxonomy that is based on the FTE typology and the OpenFlow attributes each typology models to categorise and study the different approaches to FTE representation. We apply this taxonomy to classify different projects and research works reported in the literature. Furthermore, we relate the FTE representation to use cases in practice and analyse how the representations facilitate research in SDN.

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