DynamiTE: Dynamic Traffic Engineering in Software-Defined Cyber Physical Systems

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***Abstract*—Next-generation cyber physical systems (CPS) face a variety of challenges in terms of networking, interoperability and scalability in the presence of heterogeneous devices. Recent advances in software-defined networking (SDN) make it a viable approach towards addressing these issues by introducing programmability and flexibility in the network. However, the elasticity of scale required by CPS raises some concerns about the control-overhead of the OpenFlow protocol.**

In this paper, we propose a dynamic traffic engineering scheme, DynamiTE, in software-defined cyber physical systems (SD-CPS). Our aim is to minimize the control overhead at the SDN controller by minimizing the number of PACKET-IN messages. We propose a greedy heuristic approach to determine the *optimal* number of switches required to have higher ternary content-addressable memory (TCAM), termed as *candidate switches*, compared to the other switches in the network. In such a scenario, a fully occupied switch directly forwards a new incoming flow to a candidate switch without sending a PACKET-IN message to the SDN controller. Further, a packet-tagging method is applied to notify the SDN controller about the congestion occurred at the fully occupied switch. Simulation results show that DynamiTE is capable of reducing the number of PACKET-IN messages by 10% compared to the OpenFlow-based reactive forwarding schemes (OFS). Further, the number of packets experiencing congestion in the network is reduced by 38%, compared to the randomized forwarding scheme (RFS).

***Index Terms*—Traffic engineering, Software-defined networks, Heuristic optimization, Packet-tagging, Cyber physical system**

I. Introduction

Cyber physical systems (CPS) refer to the convergence of computing, control, and communication technologies to develop the next generation engineered systems. The field of CPS integrates the dynamics of physical processes with abstractions of mathematical modeling and software to achieve autonomous control and sensing systems that are efficient, reliable, secure, robust, and scalable [1]. Next generation CPS typically include heterogeneous devices, which pose challenges in terms of networking, interoperability, and scalability. Moreover, in a large-scale environment, the interaction between systems are much more complex compared to the small-scale ones [1]. To support such requirements, improved software and networking model that addresses the above mentioned issues in a simplified manner is required. Recent advances of software-defined networking (SDN) make it a viable approach to address such networking, interoperability, and scalability issues.

OpenFlow [2], the *de-facto* standard used to realize SDN, introduces programmability into the network by abstracting the control plane from the data plane through the use of rule-based forwarding. A switch forwards an incoming flow based on the flow-rule decided by SDN controller. The flow-rules are typically placed in a flow-table at the switch using the OpenFlow protocol. To achieve *wire-speed* packet processing, the switches typically store such rules in ternary-content-addressable memory (TCAM)[1]. However, the size of the TCAM available at a switch is limited due to high energy consumption and associated cost [3]. As a result, few thousand rules can be inserted utilizing the TCAM. In the context of CPS, which require high elasticity of scale, the constrained memory presents a fundamental challenge in realization of software-defined CPS (SD-CPS).

On receiving a new traffic, the switch sends a PACKET-IN message to the controller. Consequently, the controller implements the flow-rules at the switches based on the available rule capacity, while considering other parameters as well. If rule-capacity is fully utilized at the switch, an existing flow-rule is deleted, and the new one is inserted without considering the status (i.e., active or passive) of the existing flow-rule. As a result, once the switch receives a packet associated with the deleted flow-rule again, it sends the PACKET-IN to the controller, and the same procedure is followed. Consequently, control message overhead increases, as the flow-rules are deleted and inserted in a round-robin manner.

Recently, Qiao et al. [4] proposed a scheme in which a switch randomly forwards the traffic to one of its outgoing ports, instead of sending the PACKET-IN to the controller, while its rule capacity is fully utilized. Therefore, control overhead between switches and controller is reduced to a certain extent. Figure 1 presents such a scenario, where the fully occupied switch has three different options to forward the traffic. However, as depicted in Figure 2, the scheme proposed by Qiao et al. [4] has the following limitations: a) as the outgoing port

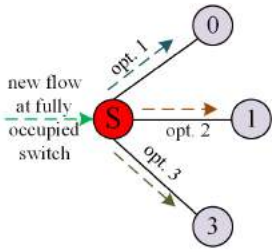


Fig. 1: An example of the scheme proposed by Qiao et al. [4]

[1]Ternary content-addressable memory (TCAM) is a fast processing memory present at SDN-enabled switches, which helps to search all available rules against an incoming traffic in a single clock cycle.

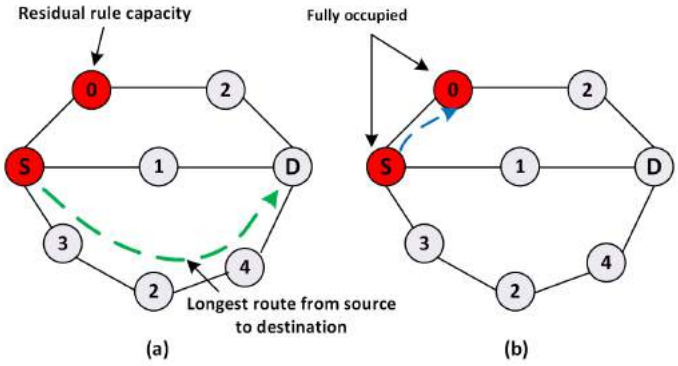


Fig. 2: Motivating scenario: Forwarding traffic to a randomly selected port may end up with — a) longest path from source to destination; and b) another fully occupied switch

for an incoming packet is chosen randomly, the packet may be forwarded through the longest path, instead of the shortest one; and b) the randomly chosen switch may also be fully occupied. In such a case, the packet is further forwarded to a switch, which is again randomly chosen. Eventually, the packet reaches to the desired destination. In such a scenario, the controller may also be unaware of such traffic flow in the network as PACKET-IN is not sent to the former.

To deal with such a problem, we propose a dynamic traffic engineering scheme in an SDN-enabled network with an aim to forward the traffic in an adequate manner, while addressing the above mentioned issues. It is noteworthy that our primary objective is to address the second issue, as mentioned in Figure 2. Addressing longest path issue is considered as secondary objective in this work. An optimization problem is formulated in the form of integer linear programming (ILP) to determine the minimum number of *candidate switches* required to forward the traffic for all possible affected[2] switches in the network. We propose a greedy heuristic approach to solve the optimization problem in polynomial time, as finding an optimal solution to the problem is NP-hard. Further, a packet-tagging approach is applied to notify the controller about the congestion occurred at a fully occupied switch. Simulation results show that the proposed scheme is capable of reducing number of PACKET-IN and congestion in the network, while placing optimal number of candidate switches.

The rest of the paper is organized as follows. Section II presents the state-of-the-art in dynamic traffic engineering in SDN. Detailed system model and problem description are presented in Section III. Further, the proposed approach for dynamic traffic engineering in SDN-enabled networks is presented. Section IV presents the simulation results to show the effectiveness of the proposed scheme. Finally, Section V concludes the paper while presenting some future research directions.

[2]Henceforth, we will use the term 'affected' for the switches, whose TCAM is fully utilized.

II. Related Work

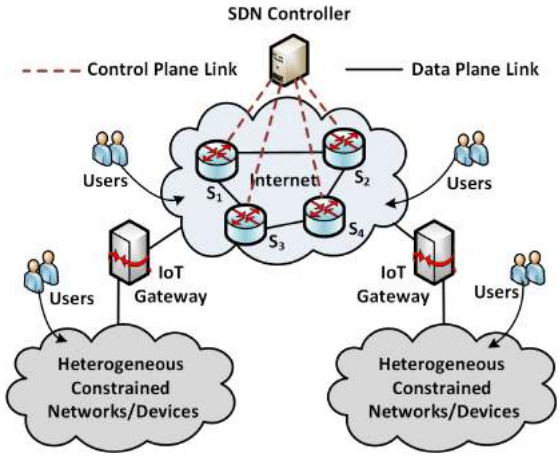
In this Section, we present the state-of-the-art for traffic engineering in SDN which can be applied to address the challenges present in CPS. Several schemes exist in the literature for traffic engineering [4]–[12]. For example, the benefits of incorporating software-defined networking concepts in traffic engineering is studied in [6]. The authors showed that the SDN-based approach is capable of forwarding network traffic in an optimal manner, while leveraging the global view of the network. Additionally, the authors formulated an optimization problem for controller placement to place flow-rules at the SDN switches deployed in the network. Caria et al. [5] analyzed the performance of network migration for traffic engineering in SDN for a given network topology. The authors proposed an algorithm to select optimal number of switches, which are required to be substituted by SDN switches, so that the need for network capacity upgradation is minimized. The proposed scheme consists of two phases — a) candidate paths selection, and b) optimization of the candidate paths. In the candidate path selection phase, all possible alternative paths are determined for a given network topology. In the second phase, the optimized paths are selected from all possible alternative paths. Consequently, the authors showed that optimal traffic engineering can be obtained while substituting a subset of the general switches by SDN switches.

Segment routing is another important aspect in traffic engineering by simplying the forwarding mechanisms. More particularly, a source node is able to specify a unicast forwarding path using the segment routing rather than specifying a shortest path, through which the packet will traverse. It is noteworthy that the segment routing was designed for SDN, while providing simplicity and better utilization of network resources in packet forwarding. Authors in [7]–[9] proposed a segment routing-based traffic engineering scheme in SDN-enabled networks, in which an architecture for segment routing is also presented. In segment routing, the SDN switches forward a packet to its next-hop switch without sending PACKET-IN to the controller. Thus, frequent rule placement at the switches can be avoided. Such an approach is useful while rule capacity of an SDN switch is nearly/completely utilized.

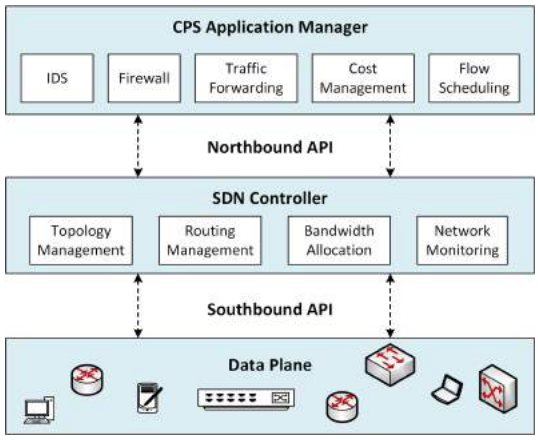
However, *detailed analysis* of the existing approaches on traffic engineering reveals that there is a need to propose a dynamic traffic engineering scheme to deal with the issues mentioned in Section I. Therefore, we propose a dynamic traffic engineering scheme for optimally forwarding network traffic in SD-CPS.

III. Dynamic Traffic Engineering

We consider an SDN architecture consisting of SDN-enabled switches/routers, controller, heterogeneous constrained networks/devices, and end-users. Typically, the heterogeneous constrained networks/devices are connected to the backbone network through IoT gateways. Figure 3 shows the network architecture considered in this work. Figure 3(a) shows a schematic architecture of SDN consisting of heterogeneous devices. Further, Figure 3(b) depicts the software-



(a) A schematic architecture of software-defined network



(b) A schematic architecture of Software-defined cyber physical systems

Fig. 3: Network architecture

defined cyber physical systems, while considering different applications and application programming interfaces (APIs) [13]. In this work, our primary focus is traffic engineering at the backbone networks, while considering incoming heterogeneous traffic from devices present in CPS. The SDN switches simply forward an incoming traffic to another switch, based on the flow-rule decided by the SDN controller. If a flow-rule associated with a traffic does not exist at the switch, the switch sends a PACKET-IN to the SDN controller. Typically, the PACKET-IN message contains *Header* of the message with fields *length*, *flow-table ID*, and *data*. After receiving the PACKET-IN, the controller places adequate flow-rules at the switch, and the traffic is forwarded based on the decided policies.

Candidate Switch: We define an SDN switch, S, as candidate switch (CS), C, if it satisfies the following properties:

- $S_{tcam} > \Gamma$, where S_{tcam} and Γ denote the TCAM memory size of the SDN switch S and a predefined threshold memory size, respectively.
- The switch has more than one neighbor in its one-hop distance, i.e., $|S_{neigh}| > 1$, where $|S_{neigh}|$ defines the number of neighbor switches in one-hop distance.

Assumption 1. *We assume that the network is fully SDN-enabled, i.e., all the switches are SDN switches. For simplicity, we consider a single SDN controller, which controls all the switches in the network. However, multiple controllers can be placed to control the switches by forming network clusters.*

Assumption 2. *All the SDN switches support OpenFlow protocol [2] for flow-rule placement. Therefore, we utilize the benefits of the OpenFlow protocol for the proposed traffic engineering and packet-tagging approaches.*

A. Problem Statement

Let there be an SDN-enabled backbone network consisting of a set of SDN-enabled switches, which is represented as $\mathcal{S} = \{S_1, S_2, \ldots, S_n\}$, $n \in Z^+$. Our objective is to find out the minimum number of switches from $\mathcal{S}$ that need to be replaced with CS, so that the traffic from a fully occupied switch can be forwarded to the CS without generating the PACKET-IN at the former. The set of CS is represented as $\mathcal{C} = \{C_1, C_2, \ldots, C_k\}$, where $k \in [0, |\mathcal{S}|]$ and $\mathcal{C} \subseteq \mathcal{S}$. Mathematically,

$$\text{Minimize } |\mathcal{C}|$$

$$\text{subject to}$$

$$\sum_{j \in \mathcal{S} \setminus \mathcal{C}} \beta_{i,j} \geq 1, \text{ for each } i \in \mathcal{C}, \tag{1}$$

$$\sum_{i \in \mathcal{C}} \beta_{i,j} = 1, \text{for each } j \in \mathcal{S} \setminus \mathcal{C}, \tag{2}$$

where Equation (1) denotes that there exists at least one CS located at one-hop distance to which the traffic can be forwarded from a fully occupied switch, $j \in \mathcal{S} \setminus \mathcal{C}$. $\beta_{i,j}$ is a binary variable used to capture the availability of such CS, $i \in \mathcal{C}$, from a switch, $j \in \mathcal{S} \setminus \mathcal{C}$. Mathematically,

$$\beta_{i,j} = \begin{cases} 1, & \text{if there exists a link between} \\ & \text{switch, } j \in \mathcal{S} \setminus \mathcal{C}, \text{ to CS, } i \in \mathcal{C} \\ 0, & \text{Otherwise} \end{cases} \tag{3}$$

Equation (2) ensures that the number of active links between a fully occupied switch, $j \in \mathcal{S} \setminus \mathcal{C}$, to CS, $i \in \mathcal{C}$, is one, so that redundancy of CS is avoided.

B. Greedy Heuristic Algorithm

The optimization problem presented in Section III-A is an integer linear programming (ILP) problem consisting of binary variables. Finding an optimal number of CS required to forward the traffic from a fully occupied in the network is an NP-hard problem [14]. Consequently, we propose a greedy heuristic approach to solve the optimization problem in polynomial time. We consider two attributes associated with each switch $S \in \mathcal{S}$ as $S.flag$ and $S.neigh$. $S.flag$ denotes whether a switch is considered to be a CS, and $S.neigh$ denotes the number of neighbors of S. Algorithm 1 presents the proposed greedy heuristic algorithm. Time complexity of the proposed greedy algorithm consists of three phases – adjacency matrix

Algorithm 1: Greedy Heuristic Algorithm

Input: Set of switches, $\mathcal{S}$; Adjacency matrix, $\mathcal{M}$; An array, A, with size $|\mathcal{S}|$
Output: Set of CS, $\mathcal{C}$

Set $\mathcal{C} = \phi$, $S.flag = 0\ \forall S \in \mathcal{S}$;
Sort all the switches $S \in \mathcal{S}$ in descending order according to the number of their neighbors using $\mathcal{M}$, and put them in A;
for $i = 1$ *to* $|\mathcal{S}|$ **do**
  if $A[i].flag == 0$ && $A[i].neigh > 1$ **then**
    $\mathcal{C} = \mathcal{C} \cup \{A[i]\}$;
    for $j = i + 1$ *to* $|\mathcal{S}|$ **do**
      if $\beta_{A[i],A[j]} == 1$ **then**
        $A[j].flag = 1$;
Return $\mathcal{C}$;

formation, sorting and greedy algorithm. The running time complexities for adjacency matrix formation and sorting are O($|\mathcal{S}|^2$) and O($|\mathcal{S}|log|\mathcal{S}|$) having $|\mathcal{S}|$ number of switches in the network. The running time complexity for greedy approach is $O(|\mathcal{S}|^2)$. Therefore, total running time complexity of the proposed algorithm is $\big(\text{O}(|\mathcal{S}|^2) + \text{O}(|\mathcal{S}|log|\mathcal{S}|) + O(|\mathcal{S}|^2)\big) \Rightarrow \text{O}(|\mathcal{S}|^2)$.

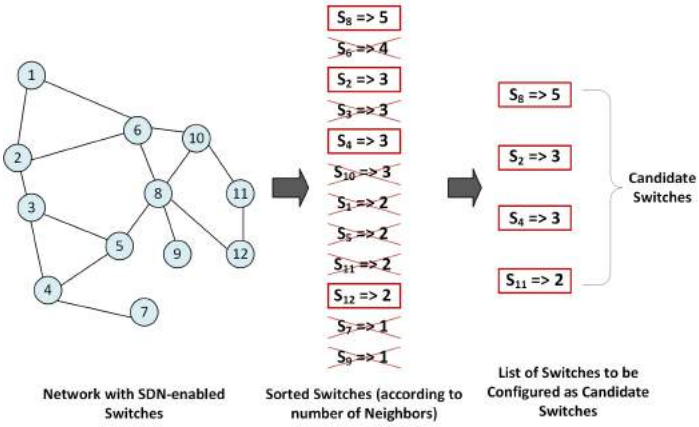


Fig. 4: Example: greedy heuristic approach for CS selection for a given network

Example: Figure 4 shows an example of selecting CS for a given network using greedy heuristic approach. In the example, part of the *Bandcon* [15] network topology is considered.

C. Tagging the PACKET-IN Message

We consider a modified version of OpenFlow protocol for sending PACKET-IN to the controller. Figure 5 shows different fields present in a PACKET-IN generated from an SDN switch according to OpenFlow protocol specification [16]. We use another **name** as **f-tag** in the **reason** field, and the **value** is set as **0X03** to notify the controller that a packet is received by a CS from a fully occupied switch. It is noteworthy that the

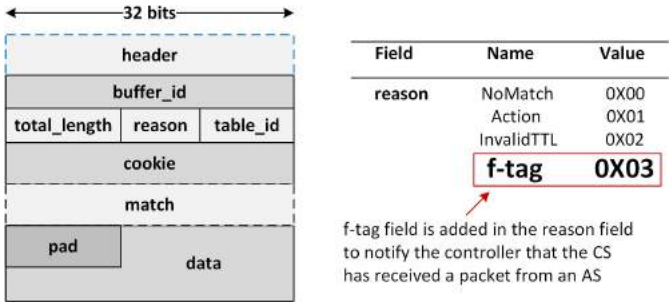


Fig. 5: PACKET-IN message sent to the controller

TABLE I: Simulation parameters

Parameters	**Value**
Network Topology	AttMpls [15]
Rule Capacity	460 (HP S-2920) & 1526 (HP S-3500) [3]
Source & Destination	Uniform Random
Number of Packets	22000 – 32000
Flow-Rule Placement	Exact-Match

f-tag is used by the CS only. This method helps the controller to minimize the congestion at the fully occupied switch further by placing the flow-rules in such a manner that new packets are not forwarded to the particular fully occupied switch. It is noteworthy that the proposed approach can easily be integrated atop the existing SDN, in which OpenFlow is used as the communication protocol between the switch and the controller.

IV. Performance Evaluation

To evaluate the performance of the proposed scheme, we consider the *AttMpls* network topology [15]. The number of nodes and links present in the network are 25 and 56, respectively. Different parameters considered to conduct the experiment are summarized in Table I.

We consider the rule-capacity of switch and CS as 460 and 1526 according to the hardware support of HP S-2920 and HP S-3500 switches, respectively [3]. For flow-rule placement, we consider *exact-match* for all packets in the network. It is noteworthy that some of the packets have the same property, i.e., all fields in two different packets may be same. Therefore, a single flow-rule is applied for multiple packets in order to take desired action. We first determine the number of CS required for a given network topology. Accordingly, we present the results for number of CS required for different network topology. Further, we evaluate the number of switches, which are fully occupied, with different number of packets using the *AttMpls* network topology.

To show the effectiveness of the proposed scheme, we evaluate the number of PACKET-IN and number of *congestion* scenarios in the network. It is noteworthy that we use the *AttMpls* network topology to present the results for PACKET-IN and congestion. Number of congestion scenarios represent the number of packets that experienced congestion at

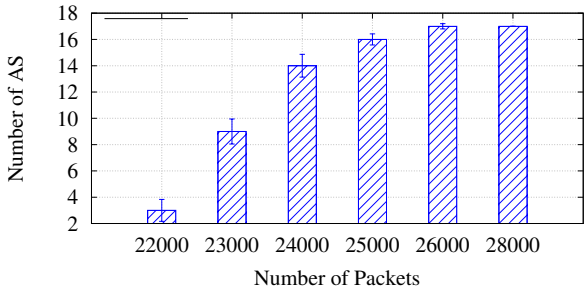


Fig. 6: Number of fully occupied switches with different number of packets in AttMpls network

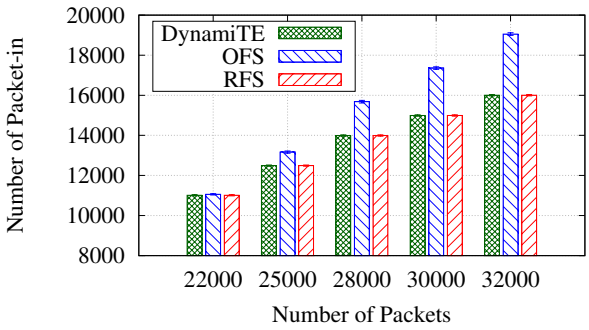


Fig. 7: Number of PACKET-IN with different number of packets in the AttMpls network

switches due to the rule-capacity constraints. We compared the performance of the proposed scheme with two different schemes — OpenFlow-based forwarding (OFS) and Randomized forwarding (RFS) [4]. In OFS, an existing rule is replaced by a new one, if the rule-capacity of the switch is fully occupied. On the other hand, in RFS, the packet is forwarded to a randomly selected outgoing port without sending the PACKET-IN to the controller. Henceforth, we use the terms OFS and RFS to denote the existing schemes.

We evaluate the number of candidate switches required to forward the traffic from a fully occupied switch in the network according to the optimization problem and the proposed solution presented in Section III. The required number of CS in AttMpls network is 8. Therefore, eight switches are placed as CS with higher TCAM, and remaining switches are placed as normal switches with lower TCAM, as mentioned in Table I.

A. Number of Fully Occupied Switches

Figure 6 shows the number of fully occupied switch with different number of packets using AttMpls network. We see that the number of fully occupied switch increases with an increase in the number of packets in the network. Finally, all the switches except CS are fully occupied with large number of packets in the network, and they forward traffic to the CS.

B. PACKET-IN Message

Figure 7 shows the total number of PACKET-IN received by the controller with different number of packets in the network. We see that less number of PACKET-IN is sent to the controller using the proposed scheme, DynamiTE (proposed), and the existing scheme RFS. However, DynamiTE outperforms the OFS scheme in terms of the number of PACKET-IN sent to the controller. In DynamiTE and RFS, a switch does not send the message to the controller, if the rule-capacity is fully occupied. Therefore, the flow-rule associated with an active flow is not deleted. In contrast, the switch always sends the PACKET-IN on receiving a new packet without considering the residual rule-capacity. Consequently, more number of PACKET-IN is received by the controller using OFS than that of using DynamiTE (proposed) and RFS. Therefore, with more number of devices in the next generation CPS, it is expected to have more number of heterogeneous packets, which, in turn, will generate more number of of PACKET-IN messages. From this aspect, we believe that the proposed scheme is beneficial to reduce the controller overhead in an SD-CPS.

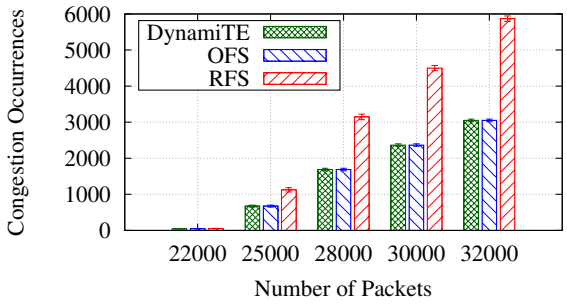


Fig. 8: Number of congestion occurred with different number of packets in the AttMpls network

C. Congestion

Figure 8 denotes the number of packets that experienced congestion in the network using different schemes — DynamiTE (proposed), OFS and RFS. We see that the number of packets that experienced congestion is the same for DynamiTE (proposed) and OFS. On the other hand, it is higher in case of RFS than that with the DynamiTE (proposed) and OFS schemes. In RFS, the packet is forwarded to a randomly selected switch, which can be further congested. Consequently, we have more number of congestion instances occurring using the RFS scheme. Similar to the PACKET-IN (refer to Section IV-B), congestion at switches will indirectly lead to a higher end-to-end delay in packet delivery. However, modern applications in CPS necessitate the packets to be delivered in real-time. From the results, it is evident that the proposed scheme is useful to reduce the end-to-end delay by reducing the number of congestion in the network.

Finally, we see that the proposed scheme, DynamiTE, outperforms the existing schemes — RFS and OFS — in terms of the number of PACKET-IN and the number of congestion instances in the network, respectively. The proposed scheme is

capable of reducing the number of PACKET-IN and congestion in the network by 10% and 38%, respectively.

V. Conclusion

In this paper, we proposed a dynamic traffic engineering scheme, DynamiTE, in an SDN-enabled cyber physical system with an aim to minimize the number of PACKET-IN messages and congestion instances in the network. We proposed a greedy heuristic approach to determine optimal number of switches required to be configured as *candidate switches*. Further, we also proposed a packet-tagging approach to notify the SDN controller that rule-capacity of a switch is fully occupied. Through extensive simulation results, it is evident that the proposed scheme is capable of reducing the number of PACKET-IN received by the controller by 10%, compared to an OpenFlow-based forwarding scheme. Further, the proposed scheme is also capable of reducing the number of congestion instances occurring in the network due to rule-capacity constraint by 38%, compared to the existing randomized forwarding scheme. To summarize, the proposed scheme is capable to addressing the challenges present in next generation CPS in terms of traffic engineering.

The candidate switches have higher TCAM compared to the other switches in the network. However, rule-space of the candidate switches can also be fully utilized in the presence of large number of packets in the network. Therefore, some of the active flow-rules are required to be deleted from the candidate switches to insert new rules. Consequently, PACKET-IN messages are generated. We plan to analyze such overflow problem at the candidate switches as the future extension of this work.

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