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# A Reliable Capacitated Controller Placement in Software Defined Networks

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***Abstract***—Software Defined Networking (SDN) is a promising area in the modern network technology giving a lot of advantages to the network operators such as programmability, high flexibility, and controllability. The control's logic is moved into a centralized remote controller. In a wide area network with multiple controllers, the number and placement of these may influence the reliability and performance of SDN. In case of controller failure, the disconnected switches must be reassigned to other working controller to maintain the network configuration and management. The propagation latency may increase due to controller failure which will lead to the increase cost of the network. In this paper, we propose a mathematical model for reliable controller placement considering it as a multi-objective problem which satisfies certain constraints. The proposed formulations are evaluated on various network topologies showing the effectiveness of the approach.

**Keywords— Software Defined Network; Controller Placement; Propagation latency; Reliability**

## I. INTRODUCTION

Software Defined Networking has created a revolution in the communication network to alleviate the problems of traditional network and vendor specific problems of network devices. The main reason is the decoupling of the control and the data plane. Such separation provides the network administrators the opportunity to create a simple, programmable, manageable and flexible system. The control logic assigned to one or more external intelligent elements called SDN controller. SDN architecture is mainly split into three distinct planes [1] [2] .

**Data Plane.** Data plane also called as infrastructure layer which consists of the forwarding elements like physical or virtual switches responsible for packet switching and forwarding accessible through an open interface.

**Control plane**. Control plane or control layer which contains a set of SDN controllers that supervises the network monitoring and management and updates the table information of switches in the flow through southbound API (Application Programming Interface).

**Management Plane.** Named also like the application layer which consists of the end user business applications. They indirectly control the forwarding elements by invoking services in the control layer through northbound APIs.

In SDN scenario, a single controller is sufficient and advantageous as one controller takes all decisions and it provides a unique view. However, its failure is a major concern. Moreover, performance and scalability will be an issue. However, to rely only on one controller for the whole network is not an intelligent solution. Therefore, the need arises for deploying multiple controllers. In multi-controller distributed scenario there are Onix, HyperFlow, Elasticon, Kandoo, DISCO and Pratyaastha which suggest the placement of multiple copies of SDN controllers in an extensive network to provide scalability and maintain the traffic load.

Controller placement problem deals with the optimal number of controllers required and their locations to manage the demands of the switches in an efficient and cost effective manner. This is similar to the facility location problem as illustrated by Heller et al. [3]. They examined the influence of switch to controller propagation latency for placement of controller. G. Yao et al. [4] consider the controller capacity while addressing the controller placement problem. However, it does not consider reliability as a metric while placing controllers. Failure of a controller results in disconnection between the switches and its controller which need to be reassigned to other working controller with enough capacity to maintain a global network state. Due to the centralized control the reliability of the control plane is a major research challenge.

In this paper, we propose a mathematical model for controller placement called reliable capacitated controller placement problem. We consider a wide area network with a fixed number of nodes and a set of controllers are there to manage them. Here, we have assumed that each node in the network acts as the probable location for installing controller, i.e., the controller and the switch can deploy in the same place. Considering node failure, we maintain a list of backup controllers for every switch at different reliability level.

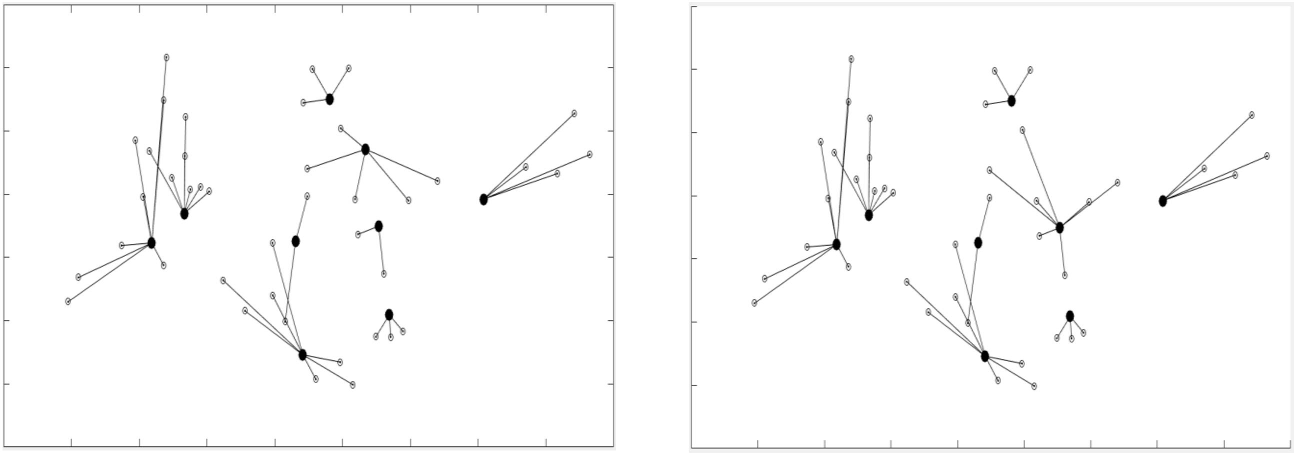


Fig.1. IRIS Network with 51 nodes data set (Without Failure) and (With one Failure)

Besides considering node failure our focus is also on the propagation latency between the switches and their assigned controllers, the incurred load of the switches on the controller and the capacity of the controller. The objective is to minimize the total cost which includes the set up cost of controllers, the routing/linking cost of controller with switches and the re-linking cost after failure of a controller.

The propagation latency of IRIS network (51 nodes) without and with one controller failure is shown in Fig.1. The switches are assigned to their nearest controller called the primary controller. When a node failure occurs, the switches are disconnected from their primary controller. They need to be assigned to other active controllers with enough capacity. Due to this the propagation latency will increase which will lead to the increase cost of the network.

This paper is organized as follows. The literatures of controller placement as addressed by different authors are presented in section II. Problem statement and proposed model are mentioned in section III. Section IV analyzes the performance of the proposed solution using real network topology. Section V concludes the work.

## II. RELATED WORK

Heller et al.[3] illustrated the controller placement problem in SDN. They consider average and worst case latency for placement of controller by taking real world topology. Yao et al.[4] consider both the load of the controller and latency while addressing the capacitated controller placement problem. In [5], Long Yao et al. considered the node weight and the delay from switches to the controller as a placement metric in a single domain. They proposed a technique to release the load of the controllers by migrating boundary switches with their cooperating neighbors. Sallahi et al.[6] proposed a technique to find the optimal number of controllers, their locations and the heterogeneity of controller types. Their aim is to reduce the network cost. While doing this, they have considered the constraints such as the capacity of controllers, ports available in a controller and network traffic patterns, etc. However, this model is suitable for small scale SDN.

Lange et al.[7] addresses various performance metrics while finding the location of controllers in large scale networks. These parameters include latency between the switches and the controller, inter controller latency, load balancing, link or node failure. Thus, it needs a trade-off between them. Hu et al.[8][9] addressed the issue of placement of controllers by taking reliability as a metric. According to them, greedy algorithm based placement provide a solution that is close to optimal. Again in 2013, they proposed a reliability-aware controller placement solution which shows tradeoffs between reliability and latencies. According to them placement of too many or too few controllers reduces reliability. Hock et al.[10] proposed a controller placement in which they considered the inter-controller latency and traffic load balancing. Like Hu et al. they consider the reliability of the control plane. Their approach is suitable for the small and medium scale SDNs. Like Heller et al. they argued that in most of the cases a single a controllers are required to maintain the network resiliency.
Ros et al.[11] introduced a placement problem in SDN. They proposed a heuristic algorithm that calculates the placements with minimum cost. They also heuristically search for what network nodes are under which controller to achieve reliability. Tanha et al.[12] proposed a formulation for resilient controller placement which cover more than one resilience level. They have considered the flow setup latency, the incurred load by the switches on the controller and its capacity while doing placement of controllers. A capacited next controller placement was proposed by Killi et al. [13] considering controller failures. The objective is to minimize the maximum worst case latency in case of controller failures taking two indexed and three indexed variable. While reassigning switches of the failed controller they have considered the closet assignment constraint. They proposed a simulated annealing algorithm to solve their problem.

TABLE 1. NOTATIONS

| Symbol | Description |
|---|---|
| $G(N,L)$ | Physical network |
| $S$ | Set of nodes/switches in the network |
| $L$ | Set of physical links |
| $C$ | Set of controllers to be deployed in the network |
| $P$ | Potential locations for deploying controllers |
| $l_i$ | Number of the requests generated by switch $i$ |
| $k_j$ | Capacity of controller $j$ |
| $d_{ij}$ | Propagation latency between switch $i$ and controller $j$ |
| $f_j$ | Setup cost for placing controller at location $j$ |
| $fp$ | Probability of controller failure |

## III. PROBLEM STATEMENT AND FORMULATION

### A. *Notations*

We represent the network as an undirected connected graph $G = (N, L)$ in which number of nodes $N = \{1, 2, ..., n\}$ and the communication links as $L = \{l_1, l_2, ...\}$. The number of nodes be $n$, where $n = |N|$. Let $N = S \cup C$, where the set of switches be $S = \{s_1, s_2, ..., s_n\}$, the set of controllers be $C = \{c_1, c_2, ..., c_p\}$ and $p$ be the probable position for hosting the controllers.

The network consists of a set of nodes placed at different locations, $d_{ij}$ is the distance (propagation latency) between nodes where $\{d_{ij} \mid i, j \in N \wedge d_{ii} = 0, d_{ij} = d_{ji}\}$. In a network with a given set of controllers located at $P$, the rest are the switches which will be assigned to the controller having shortest distance. We assume that all the switches act as the potential location for deploying controller. The load of the $i^{th}$ switch is denoted by $l_i$ for processing PACKET_IN messages. The capacity of a controller $j$ is denoted as $k_j$.

Let the decision variable used in the model be $X_j = 1$, if a controller is placed at location $j$, otherwise $0$. Similarly, let $Y_{ijr}$ (assignment variables) as $1$ if switch $i$ is assigned to controller $j$ as a $level-r$ assignment, $0$ otherwise.

A $level-r$ assignment indicates the reliability level by which a controller is connected to the switch. For $r = 0$, Indicates the primary controller is assigned to the switch, $r = 1$ denotes the first backup controller is assigned to the switch. Each switch $i$ has $r$ assigned level where $r = 0, 1, 2, ..., m-1$, and $m$ denotes the maximum reliability level.

### B. *Reliable Capacitated Controller Placement Problem*

The objectives are as follows:

$$z1 = \sum_{j \in C} f_j X_j + \sum_{i \in S} \sum_{j \in C} l_i d_{ij} Y_{ij0} \tag{1}$$

$$z2 = \sum_{i \in S} \sum_{j \in C} \sum_{r=0}^{m-1} l_i d_{ij} fp^r (1 - fp) Y_{ijr} \tag{2}$$

where $f_j$ is the set up cost of placing controller at site $j \in C$. On the occurrence of a controller failure, the switches should be connected to the backup controller with enough capacity. Due to this reassignment, the cost of the network will increase. The objective is to minimize this reassignment costs. We assume here that all controllers have a failure probability $fp$ and they fail independently from each other.

Objective $z1$ computes the setup cost for deployment of controllers and the expected routing cost of connecting the switches from their primary controller. Objective $z2$ calculates the expected routing cost after failure of the primary assignment (i.e., reassignment cost).

The RCCP optimization problem is as follows:

$$\min imize \quad \alpha z1 + (1 - \alpha) z2 \tag{3}$$

where $0 \le \alpha \le 1$.

Subject to the following constraints:

**Unique Constraint.**

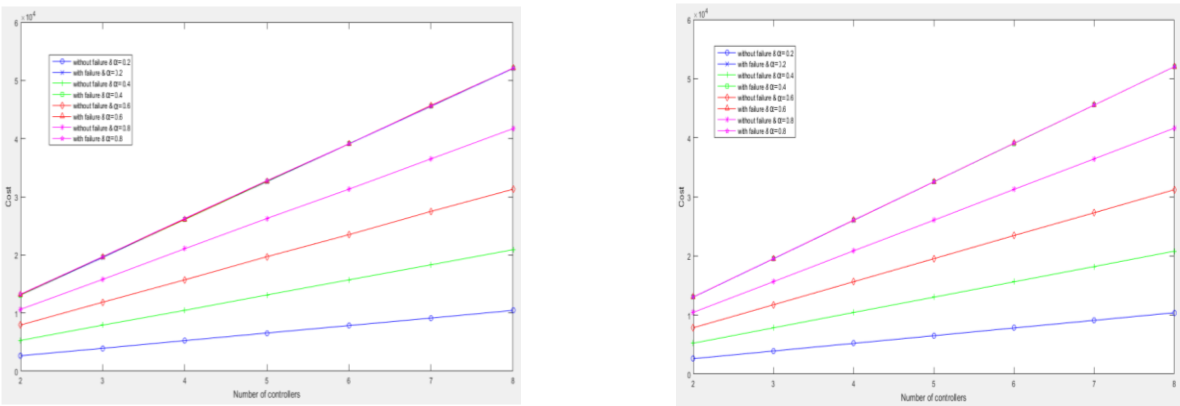
It ensures that a switch $i, i \in S$ is managed by a controller $j, j \in C$ at level $r$. $r = 0$, means a switch is attached to the primary controller. For $r > 0$ is the backup assignment.

$$\sum_{j \in C} Y_{ijr} = 1 \qquad \forall i \in S, r = 0, ..., m-1 \tag{4}$$

**Assignment Constraint.**

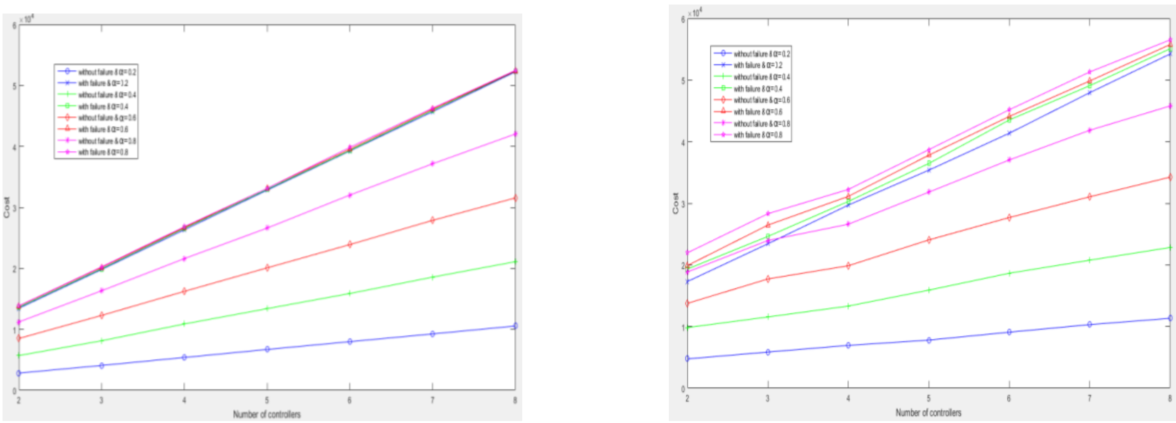
It restricts a switch from being connected to a controller which is not open.

$$Y_{ijr} \le X_j \qquad \forall i \in S, j \in C, r = 0, ..., m-1 \tag{5}$$




(a) SPRINT (11 Nodes) (b) NSFNET (13 Nodes)

Fig. 2. Impact of weight on the cost of the network without and with controller failure in SPRINT and NSFNET networks




(a) AGIS Backbone (25 Nodes) (b) JANET Backbone (29 Nodes)

Fig. 3. Impact of weight on the cost of the network without and with controller failure in AGIS and JANET Backbone networks

**Limiting from being assigned to more than one level.**
It restrains a switch from being assigned to a controller at more than one level.

$$\sum_{r=0}^{m-1} Y_{ijr} \leq 1 \qquad \forall i \in S, \forall j \in C \tag{6}$$

**Capacity Constraint.**
This indicates the total incurred load of the switches for which $j$ is the $level-r$ controller where $r = 0,1,\ldots, m-1$ should be less than $j's$ capacity where $j \in C$ .

$$\sum_{i \in S} \sum_{r=0}^{m-1} l_i Y_{ijr} \leq k_j X_j \qquad \forall j \in C \tag{7}$$

**Integrality Constraint.**
Integrality constraint guarantees the binary nature of the decision variables.

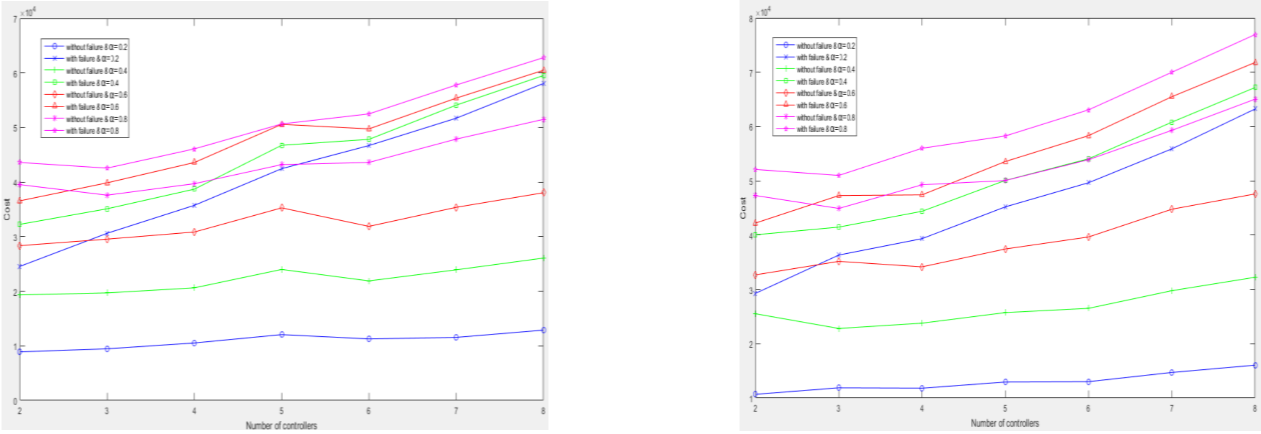
$$X_j \in \{0,1\} \qquad \forall j \in C \tag{8}$$

$$Y_{ijr} \in \{0,1\} \qquad \forall i \in S, \forall j \in C, r = 0,\ldots, m-1 \tag{9}$$

This problem is similar to the Reliability Models for Facility Location [14] where customers can play the role of switches and controllers are the facilities. In [15] the authors assumed a set of facilities that are failable and a set of facilities that are non-failable which is different from our case. We also assume here that $m << |C|$ for $level-r$ assignment.

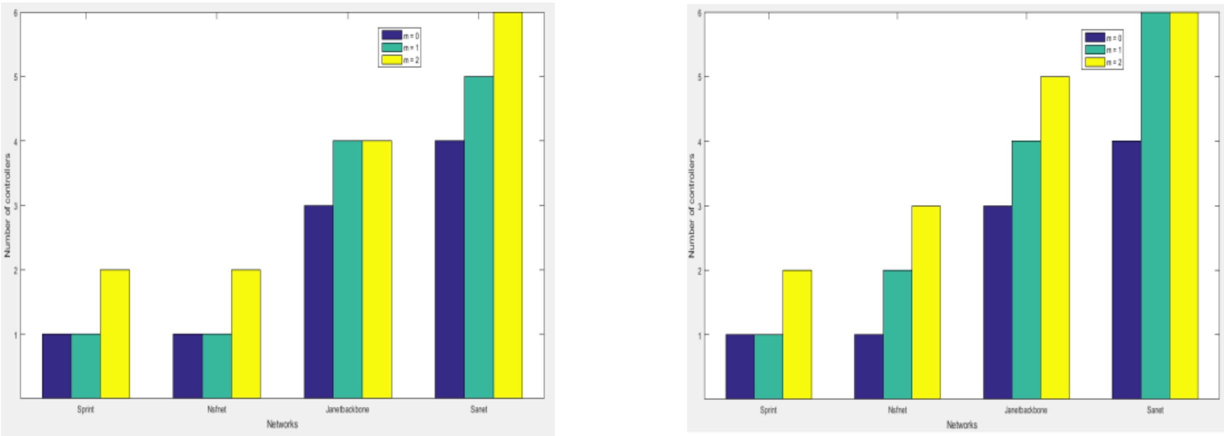
## IV. PERFORMANCE EVALUATION

The proposed RCCP formulation is evaluated on various WAN networks available in The Internet Topology Zoo. The networks include: SPRINT (11 nodes), NSFNET (13 nodes), AGIS (25 nodes), JANET Backbone (29 nodes), SANET (43 nodes) and IRIS (51 nodes). The graphML carry the latitude and longitude information which are used to calculate the propagation latency. Haversine formula gives the shortest distance between two points on the surface of the sphere and the adjacency matrix is prepared. For our implementation, we have written the program in MATLAB 2015 and run it on a machine loaded with Intel(R) Core(TM) i7 processors with 64 GB RAM.




(a) SANET (43 Nodes) (b) IRIS (51 Nodes)

Fig. 4. Impact of weight on the cost of the network without and with controller failure in SANET and IRIS networks




(a) Scenario 1 (b) Scenario 2

Fig.5. Number of controllers required in each topology at different reliability level for Scenario 1 and Scenario 2

TABLE 2. Information of Networks

| Networks | Sprint | Nsfnet | Janet Backbone | Sanet |
|---|---|---|---|---|
| No. of Nodes | 11 | 13 | 29 | 43 |
| No. of Links | 18 | 15 | 45 | 45 |
| Average Node degree | 3.27 | 2.3 | 3.103 | 2.093 |

For our evaluation, we consider the load of each switch i.e., the number of packets that are sent to the controller from $[200 - 600]$ kilo req/s. The capacity of a controller is set to be $5000$ kilo req/s. We have taken a fixed cost for placing a controller at its particular location. The probability of controller failure $fp$ is taken from $[0.01 - 0.25]$ [16] [17].

In SPRINT, NSFNET and AGIS networks, the impact of the parameter $\alpha$ without and with controller failure is shown in Fig.2. The weight $\alpha$ associated with the cost of the network without failure increases with the value of $\alpha$. Therefore, the cost of the network increases with the value of $\alpha$. The weight $(1 - \alpha)$ associated with the cost with failures remains almost the same for different values of $\alpha$ as these are small networks with less number of nodes.

In Janet Backbone network with 29 nodes and 45 links the weight of $(1 - \alpha)$ associated with the cost with failures slightly increases with the increasing value of $\alpha$ which is quite distinct in SANET(43 nodes, 45 links) and IRIS networks(51 nodes, 65 links) in Fig. 3 and 4.

Fig. 5 shows the number of controllers required at each reliability level and for each topology. For this, we run our experiments with $m = 0$ (no failure), $m = 1$ $(r = 0,1)$ and $m = 2$ $(r = 0,1,2)$. We consider two scenarios. In scenario 1, we assume homogeneous demands for switches i.e., 400 kilo req/sec with homogeneous controller capacities (5000 kilo req/sec).

For scenario 2, we assume heterogeneous demands of switches as $[200 - 600]$ kilo req/sec and controllers' capacities $[5000 - 7800]$ kilo req/sec. The probability of controller failure is same as the previous one i.e., $[0.01 - 0.25]$.

As shown in Fig. 5 (a) and (b) the number of controllers required in Sprint and Janet Backbone networks are higher in scenario 2 compared to scenario 1 as we are going higher in the reliability level. This is due to the heterogeneous demands of the switches in scenario 2 as compared to the homogeneous demands of scenario 1. As per Fig. 5 the behavior of Sprint network is same or almost insignificant in both the scenarios as the network size is small.

## V. CONCLUSION

In this paper, we proposed a formulation for the reliable capacitated controller placement which minimizes the total cost of the network considering the capacity constraint of the controller. This problem is taken up as a multi-objective problem. The total cost includes the cost for installing controllers, the routing cost of switches and controllers and the cost to reassign the switches with the controller in case of failure. We have analyzed our formulation with the real networks available in the topology zoo showing the results at different reliability levels. In our future work we will consider the load balancing metric while solving the controller placement problem.

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