Chapter 8

Conclusions and Future Work

8.1 Conclusions

This thesis addressed different problems in SDN and Hybrid SDN. In SDN, we proposed novel and efficient approaches to improve network monitoring and management targeting three different problems.

1. *Consistent statistics collection:* The primary advantage of SDN is that the controller can program the switches to define their behavior. However, to make good decisions related to network management, the controller needs to have an updated consistent network state.

   To the best of our knowledge, no earlier work in the literature targeted the problem of consistent statistics collection in OpenFlow based SDN networks. In this thesis, we proposed a novel method, OpenSnap, to collect consistent network statistics in OpenFlow based SDN networks. OpenSnap requires the switches to send their statistics on the arrival of a special packet called marker. Current OpenFlow standard does not support this functionality. OpenSnap provides consistent statistics for OpenFlow based SDN networks with First-In-First-Out (FIFO) channels. It requires multiple rounds of execution of OpenSnap to collect consistent statistics for a network with Non-FIFO channels. Thus, the statistics collection slows down. OpenSnap triggers statistics collection using an external control packet (i.e., marker packet). If this marker packet is lost, then the whole statistics collection process

has to be restarted. Thus, this solution is not robust. To address the limitations of OpenSnap we proposed an efficient and robust method, GlobeSnap, to collect globally consistent statistics. GlobeSnap is based on a coloring mechanism. It does not require sending an external control packet (i.e., marker packet) through the data paths for statistics collection. Instead, it uses the network traffic itself for statistics collection. Thus, it reduces the monitoring overhead. The statistics collection process is not hindered by switch failure or link failure, or packet loss events. Thus, GlobeSnap is robust. The performance of the proposed solutions is evaluated in terms of percentage of consistency achieved. OpenSnap achieves 100% consistency in the network with FIFO channels and 40.33% consistency in a network with Non-FIFO channels. GlobeSnap achieves 100% consistency irrespective of the channels, FIFO or Non-FIFO. The existing methods achieves a maximum of 59.89% consistency. Consistent statistics help the controller to identify bottleneck links in advance and to measure the amount of packets lost over each link.

2. *Delay measurement:* To ensure Quality of Service (QoS), the controller has to keep track of QoS parameters like bandwidth, delay, jitter, packet loss. The existing approaches of measuring link/path delay have the following issues, data plane footprint, monitoring overhead, and scalability. In this thesis, we proposed a novel method, qMon, to monitor the queueing delay. qMon does not have any data plane footprint. It leverages the OpenFlow protocol to obtain queue statistics from OpenFlow switches at regular intervals. These statistics are then used to estimate the mean queueing delay for each interval. It requires only a single queue statistics message per switch to measure the queueing delay of all the queues of a switch. Thus, it is scalable and monitoring overhead is reduced considerably. We compared the delay measured by qMon with ping RTT (round trip time). There is a high correlation between the qMon and ping RTT values for poisson traffic and bursty traffic with large ON intervals. qMon can be used to measure link delay or path delay in OpenFlow SDN networks. Real time applications have an upper limit on the amount of delay they can tolerate. Using qMon the controller can ensure the QoS requirement of such applications in real time.

3. *Polling frequency:* In SDN, network monitoring is crucial for network management. SDN provides the flexibility to remotely monitor the underlying network by polling the network statistics. There is always a trade-off between accuracy and polling overhead. The existing approaches consider the rate of change in the polled statistics to determine the polling rate. These approaches may incur high overhead, especially when the rate of change changes linearly. Thus we take this as a motivation and propose a new method that determines the polling rate based on the change in rate-of-change. The experiments show that we are better than the state-of-the-art methods by at least 23% in terms of accuracy and cost.

In Hybrid SDN networks, we targeted the problem related to waypoint enforcement. There exist a few solutions in the literature to provide waypoint enforcement. But all these solutions achieve only partial waypoint enforcement. To leverage benefits of SDN, such as modification of packet header fields, the traffic has to traverse through at least one SDN switch. In this thesis, we proposed a framework that achieves full waypoint enforcement in Hybrid SDN networks. The proposed framework uses the unused IP addresses as virtual IP addresses. The framework maps these virtual IP addresses with real IP addresses of the network such that every packet with a virtual IP address goes through at least one SDN switch in the path to its destination. We also propose four different models for mapping the virtual IP addresses with real IP addresses. The proposed framework also provides flexibility to the network administrator to decide the percentage of waypoint enforcement that she wants to achieve. Full waypoint enforcement ensures that security and other network policies are thoroughly applied to provide better network management. It also increases the adaptability of the network with changing policies.

8.2 Future Work

The works proposed in this thesis can be extended in the following directions,

- As the network size expands, single controller would not be sufficient to handle the load. Thus, multiple controllers need to be deployed to achieve reliability at control plane. Works proposed in this thesis considers single controller deployment. These solutions can be explored for a network with multiple controllers.

- In chapter 4, we proposed a method for queueing delay measurement. To calculate the queueing delay, it uses queue statistics of last two polls. A method can be developed to store the values of the statistics w.r.t time in a switch itself between two polling intervals. This would provide more accurate measurements.

- We have proposed solutions for efficient statistics collection, such as GlobeSnap, qMon, determining the polling frequency. These solutions can be integrated into a single framework and can be used to improve QoS.

- In Chapter 7, we proposed a method to achieve full waypoint enforcement. In this work the traffic is diverted to the nearest SDN switch. A mechanism can be proposed for load balancing while enforcing waypoint enforcement such that a single switch is not overloaded with the diverted traffic.