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Control traffic balancing in software defined networks

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A B S T R A C T

To promise on-line and adaptive traffic engineering in software defined networks (SDNs), the control messages, e.g., the first packet of every new flow and network traffic statistics, should be forwarded from software defined switches to the controller(s) in a fast and robust manner. As many signaling events and control plane operations are required in SDNs, they could easily generate a significant amount of control traffic that must be addressed together with the data traffic. However, the usage of in-band control channel imposes a great challenge into timely and reliable transmissions of control traffic, while out-band control is usually cost-prohibitive. To counter this, in this paper, the control traffic balancing problem is first formulated as a nonlinear optimization framework with an objective to find the optimal control traffic forwarding paths for each switch in such a way the average control traffic delay in the whole network is minimized. This problem is extremely critical in SDNs because the timely delivery of control traffic initiated by Openflow switches directly impacts the effectiveness of the routing strategies. Specifically, the fundamental mathematical structures of the formulated nonlinear problem and solution set are provided and accordingly, an efficient algorithm, called polynomial-time approximation algorithm (PTAA), is proposed to yield the fast convergence to a near optimal solution by employing the alternating direction method of multipliers (ADMM). Furthermore, the optimal controller placement problem in in-band mode is examined, which aims to find the optimal switch location where the controller can be collocated by minimizing the control message delay. While it is not widely researched except quantitative or heuristic results, a simple and efficient algorithm is proposed to guarantee the optimum placement with regards of traffic statistics. Simulation results confirm that the proposed PTAA achieves considerable delay reduction, greatly facilitating controller's traffic engineering in large-scale SDNs.

1. Introduction

Software Defined Networks (SDNs) have been recognized as the next-generation networking paradigm with the promise to dramatically improve network resource utilization, simplify network management, reduce operating cost, and promote innovation and evolution [1–3]. One of the key ideas in SDNs is to separate the data plane from the control plane by: (i) removing control decisions from the forwarding hardware, e.g., routers or switches, (ii) enabling the forwarding hardware to be programmable through an open and standardized interface, e.g., Openflow [1], and (iii) using a network controller with the supporting management applications (such as routing and resource allocation) to define (in software) the behavior of the network forwarding

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infrastructure. With such decoupled networking architecture, the timely delivery of control messages for each software defined or Openflow switch largely impacts the efficiency and effectiveness of SDNs, especially when in-band mode [4] is used for control traffic that could significantly affects the system performance with the combined traffic of the original data and the control messages. Thus, it becomes a great challenge to support the load-balancing of in-band control traffic for the minimum network delay via a centralized controller in SDNs.

Furthermore, many signaling events and control plane operations are required in SDNs [2,3,5]. They could easily generate a significant amount of control traffic that must be addressed together with the data traffic. On the other hand, it would be cost-prohibitive to deploy large-scale SDN with out-band control where each switch would be directly connected to the controller with a separate control channel. We foresee that SDN technologies would be gradually adopted in enterprises in in-band mode, as we start to address and resolve remaining technical issues. However, existing work all focuses on balancing data traffic in data plane, such as prioritizing the interactive, elastic, and background traffic in [6]. Different from data traffic balancing which aim to evenly distribute data traffic flows among network links, control traffic balancing is much more challenging particular for in-band control [3]. It aims to find the control message forwarding paths of each switch in such a way that the control message delay can be minimized subject to acceptable performance for the original data traffic. This control traffic forwarding problem is extremely critical in SDNs because the timely delivery of control traffic initiated by Openflow switches, e.g, the first packet of every new flow and the traffic/congestion status, directly impacts the effectiveness of the routing strategies determined by the controller.

In this paper, by using queueing network theory [7], we address the control traffic forwarding issue by formulating it as *a nonlinear optimization problem*. However, the complexity of such a formulation is extremely high due to (i) its nonlinearity and (ii) massive variables of link traffic assignments for large-size networks. As a result, the conventional methods for nonlinear optimization problems, such as interior point methods [8], become impractical both in terms of computation time and storage. Therefore, the principle solving method for these large-scale nonlinear problems is to find an approximate and near optimal solution in the solution space [9]. Towards this, we first analyze the fundamental structure of control traffic balancing problem by proving its polynomial time complexity, i.e., its *polynomiality* [9]. Specifically, the optimization problem is justified as a strictly convex framework, and it is proved that the solution can be approximated by a polynomial-time fast algorithm. Furthermore, by deriving the Karush–Kuhn–Tucker (KKT) optimality conditions [8], we reveal the mathematical structure of solution set. Such polynomiality analysis along with the derived KKT conditions enable us to design a fast convergent algorithm for the control traffic balancing problem, based on the alternating direction method of multipliers (ADMM) [10], which is an emerging parallel and fast first-order method for solving large-scale convex optimization problems. In particular, we propose a polynomial-time approximation algorithm (PTAA) that applies the primal-dual update rules of ADMM approach to solve the formulated large-scale convex optimization problem. In particular, PTAA is an iterative algorithm that accurately approximates the optimal solution with fast convergence. We prove that PTAA follows the rapid convergence rate $O(1/c^m)$ with a constant $c > 1$ and iteration number m. Such fast convergence property is extremely important for SDNs because the time-varying traffic pattern in both data plane and control plane may require the fast re-planning of forwarding paths between switches and controller. Performance evaluation confirms that the proposed PTAA provides network delay for control traffic similar to the benchmarks from brute force algorithms, and outperforms the conventional single- and multi-path solutions with at least 80% delay reduction that is time-efficient and could be executed in parallel. To the best of our knowledge, this work is the first to address control traffic balancing problem in SDNs along with the provably fast-convergent algorithm to yield the near optimal solution.

In addition to the control traffic balancing problem, the controller placement problem in in-band mode is also addressed in this paper. Such problem aims to find the optimal controller location (particularly, the best attaching switch location) among all possible ones, which yields the minimum average control message delay. The controller placement problem is not widely researched in the research community to date. In particular, in [11], the distance between a controller and the switches is adopted as the performance metric and several well-known network topologies are evaluated through simulations to find the optimal controller location. In [12], the performance of four different controller placement algorithms are examined in terms of the reliability of control traffic path. Nevertheless, these efforts only look for quantitative or even heuristic results, and the qualitative analysis is still missing. Contrary to the existing solutions, we develop a simple and efficient algorithm that guarantees the optimum solution for the controller placement problem.

The rest of the paper is organized as follows. The system model is presented in Section 2. Control traffic balancing problem as well as the fundamental problem structure are examined in Section 3. To deal with such a problem, the mathematical solution structure is analyzed and the novel PTAA is proposed through fast ADMM with the further consideration of convergence analysis and the optimal controller location in Section 4. Performance evaluation is provided in Section 5 and the paper is concluded in Section 6.

2. System model

To design load-balancing for control traffic flows, we first describe the network topology of SDNs and then provide the overlaid traffic model in the following.

2.1. Network topology

Indicated by [4], a typical SDN as shown in Fig. 1 generally consists of multiple Openflow enabled switches (i.e. OF switches), which constitutes data plane, and a centralized network controller. The SDN is modeled by a network graph $G = (V, J)$ in Fig. 1b, where V is a set of OF switches with total n switches (i.e., $|V| = n$) and J is a set of links with total $|J|$ links. Rather than exploiting costly out-band control due

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