多个控制器.该文给出了对控制器放置问题进行进一步研究的必要性.

文献[65]在文献[64]的基础上,以最小化最大的控制器-交换机传输时延作为优化目标,同时考虑控制器的容量约束,对分布式控制平面的控制器放置问题展开研究.该问题被建模为有容量约束的 *k*-center 问题.文献[66]从负载均衡的角度出发,通过构建控制树进行控制器的放置,但在该文中,控制负载的衡量指标是交换机的数目.实际上,由于所连接主机的功能不同,不同交换机造成的控制负载千差万别,以交换机产生的网络请求数目来衡量控制负载更为合理.文献[67]就是以此衡量控制负载,并根据 Little 公式计算控制器负载造成的处理时延,与控制器-交换机距离带来的传输时延共同组成网络请求响应时延,作为分布式控制平面控制器放置问题的限制条件.如此设计同时满足了控制器-交换机距离和负载均衡约束,使得控制资源的分配与数据平面的处理需求分布匹配,以较小的控制资源成本实现了 SDN 网络的需求,提高了控制平面的资源利用率.文献[68]进一步考虑了分布式控制平面中控制器之间的响应性能,使用讨价还价博弈对控制器-交换机传输时延和控制器之间的传输时延进行权衡分析,设计了一种控制器放置方案.文献[69]在综合考虑上述因素的情况下,设计了一种基于交换机分布密度的聚类算法.首先将数据平面分域,再在各个域中确定其最优控制器.该算法计算复杂度较低,能够适用于大规模网络.文献[70]则探讨了一种增量部署场景,即:在现有 SDN 数据平面和控制器部署的基础上,当数据平面规模扩大时,如何以最小的成本增量式地部署足够多的新控制器,这给 SDN 网络的管理提供了更多的思路.

5.2 弹性控制

网络流量具有空间分布不均和时域动态变化的特征[30],体现到 SDN 网络,就是空间上不同交换机由于所连接主机的需求和提供的服务不同,流到达速率不同;时域上不同交换机的流到达速率按照网络需求的动态变化而变化.由于用户行为的随机性,网络流具有随机性和瞬时突发特征[30,45].分布式控制平面中固定配置的控制平面很难适应这一变化,往往导致部分控制器发生负载过重的情况,使网络事件无法得到及时响应,甚至被拒绝响应.

应对负载增加的通用思路是增加相应的处理资源,即:在控制器负载过重时对控制区域进行裂变,并增加新的控制器以适应负载的变化.这种方式虽然能够解决控制器负载过重的问题,但是对问题的考虑是一种局部的不经济的思路.应该注意到:整个 SDN 网络中,控制负载具有空间分布不均的特征,使得控制平面负载不均衡,某些控制器负载过重的同时,其他控制器可能处于空闲状态,现有控制平面的资源并未得到充分的利用.这是由于控制器-交换机映射与负载空间分布不匹配造成的.并且,由于负载分布随时间随机变化,并不能通过静态的最优映射[65]达到一劳永逸的目的.因此,更为经济优化的思路是根据负载的分布实时动态地调整控制器与交换机的映射,实现控制平面负载均衡.这种思路也称为弹性控制[71].

SDN 中,控制平面将控制资源分配到每个交换机,以处理数据平面产生的控制负载.弹性控制的思路是:根据控制负载的分布,动态地、自适应地调整控制资源在数据平面的分布.这一分布包括控制器与交换机的映射关系和控制器与所属交换机的相对位置.前者代表控制资源在数据平面的数量分布,即,交换机所拥有的控制资源总量;后者代表控制资源在数据平面的位置分布,即,交换机与其所属控制资源的距离.相应地,弹性控制技术包含对控制资源数量分布和位置分布的调整,这一调整可以通过动态部署控制平面和动态更改控制器与交换机的映射关系来实现.

DCPP[72]构建了一种控制平面动态部署方案,它根据数据平面的负载分布,动态调整控制器的数目、位置以及与交换机的映射,使其与负载的空间分布完全匹配.LiDy+[73,74]通过添加对控制负载的预测来预留足够的控制资源,根据控制负载的分布,动态调整控制器的部署,以期在控制平面成本和控制器交换机的时延之间取得折中.控制平面动态部署方案是最优的弹性控制方案,但是,这种方案需要频繁地重新部署控制平面,会带来大量的管理开销和时延,无法实时响应控制负载分布的变化,影响到网络的正常运行.

ElastiCon[71,75]给出一种温和的解决方案,它不改变当前控制平面的规模和部署,仅仅通过使交换机在控制域之间迁移来调整控制器的负载,实现负载均衡.当且仅当数据平面的整体负载与控制平面的整体处理能力不匹配时,才会调整控制器的数目.ElastiCon 还给出了无缝的交换机迁移协议及包括交换机迁移、控制器池变更

在内的弹性控制算法.

基于 ElastiCon 给出的交换机迁移协议,我们希望设计控制器-交换机重映射算法,计算最优的控制器-交换机的映射,使其与负载分布相匹配.文献[76]以控制平面负载均衡为优化目标对这一问题进行建模,并使用线性规划给出其近似解,但是线性规划求解复杂度较高,且随着网络规模的扩大,算法的可扩展性较差.文献[77]以控制资源利用率最大化为优化目标展开求解,将动态重映射过程建模为马尔可夫链,并设计了一种分布式跳转算法,将计算任务分布在不同的控制器.该算法充分发挥了各个控制器的计算能力,但是整个重映射过程信令比较复杂,收敛速度较慢.文献[78]则以最小化控制平面响应时间为目标,将重映射过程建模为多对一稳定匹配问题进行求解,之后使用组合博弈实现负载均衡.由于第 1 步缩减了组合博弈的搜索空间,使得整个求解过程迅速收敛,保障了算法的实时性,提高了算法应对数据流分布随机变化的适用性和应用于大规模网络的可扩展性.

6 总结与展望

6.1 总 结

SDN 控制转发分离的特性简化了网络的配置和管理,同时也带来了严重的可扩展性问题.本文结合分布式系统可扩展性的衡量指标来分析 SDN 控制平面的可扩展性,并给出了 4 种改善 SDN 控制平面可扩展性的思路.在此基础上,本文从数据平面缓存优化、高性能控制器、分布式控制平面和控制资源优化分配 4 种技术路线出发,分析探讨了现有 SDN 控制平面可扩展性问题的主要解决方案和研究进展.这 4 种技术路线与第 1.3 节中 4 种改善思路的对应关系见表 1.

Table 1 Correspondence between the 4 technical routes and the 4 improvement strategies

表 1 4 种技术路线与 4 种改善思路的对应关系

技术路线	改善思路
数据平面缓存优化	(1) 优化管理交换机中缓存的流表项
高性能控制器	(2) 提高控制平面的处理能力
分布式控制平面	(2) 提高控制平面的处理能力;(3) 减小控制平面和交换机之间的传输时延
控制资源优化分配	(3) 减小控制平面和交换机之间的传输时延;(4) 提高现有控制资源的利用率

6.2 展 望

当前,随着 SDN 网络的逐步推广,SDN 控制平面面临的可扩展性问题越来越严峻.尽管当前针对这一问题已经提出了一系列的解决方案,但是仍有许多关键问题亟待解决.此外,目前,SDN 还不是一个成熟的架构,随着 SDN 的持续演进,新的控制平面可扩展性解决方案会相继涌现,同时,对控制平面可扩展性问题的研究也会进一步推动 SDN 架构的不断创新.下面对未来研究重点和发展趋势进行探讨.

(1) 基于网络需求确定网络事件的处理粒度

灵活的网络控制是 SDN 的一个重要特征.这一特征主要是通过细粒度的网络请求和被动的规则安装实现的,而这两个因素对控制平面带来了较重的控制负载,是控制平面可扩展性问题的源头.然而,实际网络中,用户的通信需求往往是基于应用或服务进行划分的,网络核心对数据流的处理往往也基于聚合的原则.因此,完全细粒度的处理并不是必要的,基于网络需求来确定网络事件的处理粒度才是更合理的选择,即,对网络事件进行合理的抽象.当前,对 SDN 抽象方案的研究主要集中于高级编程语言的设计,将抽象思路拓展到南向接口,对网络控制的灵活性、数据平面和控制平面的可扩展性均具有现实的意义.

(2) 标准化交换机的控制功能

SDN 控制转发分离的思路简化了网络的配置和管理,但是很多交换机本地即可完成的控制功能只能上传至控制平面处理,给控制平面带来了较大的负担,也延长了这些网络功能的响应时间.当前,很多研究者对在交换机实现部分控制功能展开了研究,但是,由于这些方案对 OpenFlow 交换机结构和应用模式进行了修改,其推广难度较大.因此,有必要对交换机本地需要且在本地即可完成的控制功能集合进行提取,并以标准化的形式整合到 OpenFlow 交换机的软件协议栈中.应该注意的是:这一设计并不违反控制转发分离的原则,网络的控制转

发分离仍然以软硬件分离的形式实现,只是控制平面结构得到了革新,以分层控制平面的形式呈现.

(3) 弹性控制平面的资源池模型

ElastiCon[71]引用云计算中资源池化的概念对控制器池进行了描述.实际上,由于数据中心网络中虚拟化技术的发展,对 SDN 控制器的管理也可以采用资源池化的方式展开,在空间尺度和性能尺度上扩展控制平面的处理能力.同时,为了灵活、高效地管理控制资源,可以基于服务化的思想设计分布式服务框架,对控制平面功能进行模块化抽象和组合.在这一框架下,对高能效弹性控制平面、控制器部署和迁移、控制功能模块化抽象、控制功能组合等问题展开研究具有重要的意义.

(4) 面向分布式控制平面的分布式算法设计

传统网络中,由于网络设备完全分布式的部署,网络协议往往通过分布式算法实现.SDN 网络出于可扩展性考虑,引入了分布式的控制平面.对于完全分布式的控制平面和分层控制平面,在处理跨域网络事件时,由于不具备全局网络视图,往往需要沿用传统网络的分布式算法进行处理.然而,SDN 控制器仍具有域内集中控制的优势,如何利用这一优势对 SDN 分布式控制平面设计优化的分布式算法、提高控制平面可扩展性,也是未来的一个研究方向.

(5) 数据平面的多维划分

SDN 网络中,为了提高控制平面的可扩展性,往往将数据平面负载划分给多个控制器分别处理.现有研究中,主要以交换机作为数据平面划分的粒度.实际上,除了根据物理拓扑进行划分,数据平面负载还可以有多种划分方式,如根据虚拟网进行的虚拟拓扑划分、根据网络应用不同进行的流表空间划分等.不同的划分方式和划分粒度适用于不同的网络需求,有必要根据网络需求设计合理的数据平面划分,提高控制平面的处理性能和可扩展性.

(6) 网络应用感知的控制资源优化分配

SDN 控制平面的可扩展性关注的主体是网络请求,现有研究在评估控制平面负载时,也往往以网络请求的数量为依据.然而,对不同的网络请求,控制平面需要调用不同的网络应用进行处理,消耗的控制资源也就有所不同.部分应用,如网络虚拟化和流量工程等,其计算复杂度较高,消耗的控制资源较多;而接入控制、MAC 学习等应用消耗的资源较少.因此,在进行控制资源分配时,应综合考虑网络请求的资源消耗及其在网络中的分布特征,确定优化的控制资源分配方案,提高控制资源的利用率.

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