Source selection problem in multi-source multi-destination multicasting

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Multicast is designed to jointly deliver content from a single source to a set of destinations; hence, it can efficiently save the bandwidth consumption and reduce the load on the source. In many important applications, the appearance of multiple sources brings new opportunities and challenges to reduce the bandwidth consumption of a multicast transfer. In this paper, we focus on such type of multi-source multicast and construct an efficient routing forest with the minimum cost (MCF). MCF spans each destination by one and only one source, while minimizing the total cost (i.e., the weight sum of all links in one multicast routing) for delivering the same content from the source side to all destinations. Prior approaches for single source multicast do not exploit the opportunities of a collection of sources; hence, they remain inapplicable to the MCF problem. Actually, the MCF problem for a multi-source multicast is proved to be NP-hard. Therefore, we propose two \((2 + \varepsilon)\)-approximation methods, named P-MCF and E-MCF. We conduct experiments on our SDN testbed together with large-scale simulations under the random SDN network, regular SDN network and scale-free SDN network. All manifest that our MCF approach always occupies fewer network links and incurs less network cost for any multi-source multicast than the traditional Steiner minimum tree (SMT) of any related single source multicast, irrespective of the used network topology and the setting of multicast transfers.

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1. Introduction

Multicast is a natural approach to deliver the same content to a group of destinations not a single destination. It benefits in efficiently saving the bandwidth consumption and reducing the load on the sender, compared with the unicast. The root cause is that multicast can avoid unnecessary duplicated transmissions among a set of independent unicast paths towards destinations, after multiplexing a shared multicast tree. The tree spans the source and all destinations. Flows from the same source to destinations form a multicast transfer. Despite such bandwidth superiority, multicast in the Internet suffers many deploying obstacles during the preceding decades. Until recently, it achieves a few successful network-level deployments in IPTV networks [1], enterprise networks, and data center networks [2].

Among existing multicast routing protocols, PIM is the most widely used one, which connects the source and destination via a shortest-path tree. An inherent drawback of this method is that those independent shortest paths, from each destination to the same receiver, lack opportunities to share more common links.

Thus, the formed shortest-path tree fails to minimize the amount of utilized links; hence, multicast traffic along it cannot considerably save the bandwidth consumption. For this reason, many efforts focus on solving the Steiner minimum tree (SMT) [3], a NP-hard problem. It aims to minimize the total number of edges in a tree, spanning all members of any given multicast group. The SMT is not adopted by current networks, due to the huge computation overhead even under heuristic methods and the challenge of distributed deployment [4].

Such multicast methods, however, assume priori knowledge of multicast characteristics, i.e., the source of each multicast group is fixed in advance. We call this case as the single-source multicast. Unfortunately, in many cases, the characteristics of a multicast transfer are unknown a priori. That is, it is not necessary that the source of a multicast transfer has to be placed in a specific location as long as certain constraints are satisfied. A major reason is the widely used content replica designs for improving the robustness and efficiency in various networks, such as the content distribution network [5], IPTV networks, and datacenter networks [2,6]. When delivering a content file to multiple destinations, the source of such a multicast transfer can be any one replica in theory [7]. This causes the multi-source multicast, due to the source flexibility.
In this paper, we focus on a new type of multicast transfer, the multi-source multicast. Given a set of destinations and a collection of sources, together with the network topology, the multi-source multicast problem aims to construct a minimum cost forest (MCF). It ensures that each destination connects to just one source through a path in the forest. The proposed multi-source multicast is a general scheme, which is equivalent to the single-source multicast in the special setting of a single source. The objective is to minimize the cost of the constructed forest. Compared with the SMT, finding the MCF for any multi-source multicast is more challenging, due to the flexible use of multiple sources and the impact on routing. We prove that the MCF problem is NP-hard. A potential approach is to divide multi-source multicast as a set of single-source multICASTs, each with a distinct source. The SMT with the least cost among such multICASTs just acts as the MCF of the multi-source multicast. This way, however, suffers from the complexity of solving a set of NP-hard SMT problems. Moreover, the MCF under non-single sources may cause less total cost than the picked best SMT with any single source. Thus, prior approaches, relying on traditional multicast, remain inapplicable to the multi-source multicast proposed in this paper.

To solve the MCF problem efficiently, we propose two \((2 + \varepsilon)\)-approximation methods, P-MCF and E-MCF. Such methods use a part of sources to establish routing paths towards all destinations. They can seek shared nodes among such paths to enhance the possibility of aggregating more links. Thus, they can reduce the number of employed links while ensuring that the delivered content can reach each destination within an acceptable delay. We conduct small-scale experiments on our testbed and large-scale simulations to compare the multi-source multicast and traditional multicast under the random network, regular network and scale-free network respectively. The evaluation results indicate that the MCF of multi-source multicast occupies less network links and incurs less network cost, irrespective of the used network topology.

In the remainder of this paper, we present our work as follows. In Section 2, we summarize related multicast methods. In Section 3, we present the problem formulation and model of the multi-source multicast. We design two efficient approximation algorithms in Section 4, and evaluate the performance of our algorithms through evaluations and simulations in Section 5. Finally, we discuss and conclude this paper in Sections 6 and 7.

2. Related work

2.1. Approximation methods for the SMT problem

Given any single-source multicast transfer, much research work focuses on the construction of multicast trees to satisfy various constraints. The SMT problem formulates a common constraint on the multicast tree, i.e., the amount of occupied links for spanning all members of a multicast group. Many algorithms for the SMT problem have been proposed to approximate the optimal solution. A fast and effective algorithm achieves a \((2 + \varepsilon)\)-approximation, which approximates the SMT problem using a minimum spanning tree (MST) in [8]. Several methods, based on greedy strategies, achieve better approximation ratio, such as 1.746 [9], 1.693 [10], 1.55 [11], 1.39 [12], but considerably incur high time complexity than the \((2 + \varepsilon)\)-approximation algorithm. The \(k\)-restricted loss-contracting algorithm achieves a 1.55-approximation. The time complexity, however, is too high due to many rounds of iterative computation, which is hard to be terminated within the acceptable time. Actually the round of iterations is unpredictable for large-scale networks.

Although the fast SMT algorithm does not achieve the optimal approximation ratio, it significantly saves more computation time than other algorithms. Hence, it is more suitable than other algorithms for large multicast groups and large-scale networks. A LP-based approximation algorithm presented in [12] can achieve a better approximation ratio of 1.39. It adopts iterative randomized rounding technique and is designed on the basis of \(k\)-restricted algorithm. Hence, it suffers high computation complexity. Such SMT algorithms, however, are still inapplicable to the MCF problem proposed in this paper, due to the introduction of multiple sources for each multicast group. Those multicast algorithms have not been adopted by current networks, due to the huge computation overhead and the challenge of distributed deployment [4]. Fortunately, the emergence of SDN makes it possible to realize novel multicast protocols.

2.2. The minimum-residual-bandwidth multicast

Given a multicast transfer, the desired multicast tree may need to satisfy other essential constraints, such as the end-to-end delay constraint, the reliability constraint, and the optimal residual bandwidth. The most related research work revolves around the MMForest algorithm [13]. For a collection of multi-source multICASTs, MMForest aims to establish a multicast forest for each multi-source multicast to span its all destinations and sources, such that the shared network exhibits the maximal residual bandwidth. Actually, MMForest is designed based on the existing Widest-Path Forest algorithm, which prefers to select those links with higher residual capacity. It means that the knowledge about the collection of multi-source multICASTs is known in advance and the construction order of their forests has serious impact on the final residual capacity. That is, all multi-source multICASTs have to design their forests cooperatively.

The MMForest method focuses on optimizing the residual bandwidth under a set of multi-source multicast streams. On the contrary, the MCF problem proposed in this paper aims to tackle the widely used constraint, i.e., minimizing the amount of occupied links for each multicast stream. Thus, for a multi-source multicast, our MCF method establishes a forest with less amount of links than the MMForest method; hence, our MCF consumes less amount of total bandwidth than the MMForest. When many streams need to be delivered along different multi-source multICASTs, more links would be saved by our MCF rather than the MMForest. Thus, our MCF method can further improve the level of residual bandwidth, and make the network support more multicast forests concurrently.

Moreover, MMForest remains inapplicable to our MCF problem. The root cause is that its basic idea is similar to the most straightforward multicast tree. MMForest makes each destination select one path with the largest residual bandwidth towards all sources, and then merges those paths selected by all destinations. Obviously, this method loses non-trivial opportunities to maximize the number of shared links among individual paths. MMForest is actually one type of the shortest-path forest; hence, it incurs higher total link cost than our MCF, due to the lack of shared links.

3. Problem statement of MCF

We start with the important observation of multi-source multICAST, and then present the problem statement of multi-source multICAST. Finally, we give a mixed integer linear programming model for the multi-source multicast problem.

3.1. Observations

Multicast is a natural approach to deliver the same content to a group of destinations not a single destination. It benefits in efficiently saving the bandwidth consumption and reducing the load on the sender, compared with unicast. The total cost of a multICAST
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