The Journal of Systems and Software 136 (2018) 59–73

Contents lists available at ScienceDirect

The Journal of Systems and Software

journal homepage: www.elsevier.com/locate/jss

Broadcast tree construction framework in tactile internet via dynamic algorithm

Jiankang Ren[a], Chi Lin[b,*], Qian Liu[a], Mohammad S. Obaidat[c], Guowei Wu[b], Guozhen Tan[a]

[a] School of Computer Science and Technology, Dalian University of Technology, No 2, Linggong Road, Dalian, 116023, China
[b] School of Software Technology, Dalian University of Technology; Key Laboratory for Ubiquitous Network and Service Software of Liaoning Province. Road No. 8, Development Zone, Dalian, 116620, China
[c] Computer and Information Science, Fordham University, NY, USA

ARTICLE INFO

Article history:
Received 23 May 2017
Revised 25 September 2017
Accepted 7 November 2017
Available online 8 November 2017

Keywords:
Tactile internet
Dynamic algorithm
Rooted delay-constrained minimum spanning tree
Real-time

ABSTRACT

Extremely low-latency and real-time communications are required in Tactile Internet to transfer physical tactile experiences remotely. In addition, its traffic has stringent requirements on bandwidth and quality of service (QoS). To minimize total costs of establishing the network and satisfy a pre-defined global upper delay-bound on the paths from the server to any other client for message broadcast in Tactile Internet, this paper presents a Rooted Delay-Constrained Minimum Spanning Tree (RDCMST) construction framework based on dynamic algorithm. The network is modeled as a connected weighted and undirected graph. Infeasible and suboptimal edges are discarded first by preprocessing techniques to reduce the processing complexity of the algorithm. Then the edges of the graph are processed based on a dynamic graph algorithm, which can maintain a single-source shortest path tree for the online edge deletions, such that total costs can be minimized while ensuring the delay-constraint and the tree structure. Experimental results show that our proposed approach greatly outperforms existing competing RDCMST formation algorithms, in terms of both average cost and stability of solutions.

1. Introduction

Tactile Internet is an internet network combining extremely low latency with a high level of reliability, availability and security (Fettweis et al., 2014). It is envisioned to transport physical tactile experiences remotely, which makes the interaction between humans, machines and systems even faster and more efficient. It can enable the skillset/labor-delivery networks, and hence will bring about the social and economic revolution (Fettweis, 2014). For example, wireless controlled exoskeletons, tele-diagnosis, telesurgery, tele-rehabilitation, remote education and training, remote driving, and industrial remote servicing and decommissioning can be achieved and provided through Tactile Internet (Simsek et al., 2016; Wollschlaeger et al., 2017; Chen et al., 2017). To fully explore the potential of Tactile Internet, we need to pay close attention to a number of significant challenges (Maier et al., 2016; Tudzarov and Gelev, 2017).

Most of applications governed by Tactile Internet require extremely low-latency and real-time communications, e.g. 1ms round-trip time for manual interaction, where the traffic usually has stringent requirements on bandwidth and quality of service (QoS) (Ren, 2016; Matthé et al., 2017; Yang and Kuipers, 2012; She and Yang, 2016; Aijaz et al., 2017). Thus, many Tactile Internet applications require or can benefit from low-cost real-time broadcast support in networks (Kourouthanassis and Georgiadis, 2014). Broadcast refers to the fundamental network functionality of delivering data from a source node to all other nodes. It uses packet replication and appropriate forwarding to eliminate unnecessary packet retransmissions. This is especially important in power-constrained wireless Tactile Internet systems which suffer from interference and collision. As shown in Fig. 1, it is a simplified system architecture for the free viewpoint video, which is a killer application of Tactile Internet (Fettweis, 2014). Through the free viewpoint video, each stadium visitor can choose their viewpoint of interest, e.g. the viewpoint of the favorite player on the pitch. In the stadium, several cameras are equipped to capture the event of the animate (e.g., player) or inanimate (e.g., soccer ball) object. Once the event is captured, it is then encoded for transport, transported to a mobile edge computing (MEC) server. The edge server can perform the real-time rendering in the place close

* Corresponding author.
E-mail addresses: rjk@dlut.edu.cn (J. Ren), chilin@mail.dlut.edu.cn, c.lin@dlut.edu.cn (C. Lin), qianliu@dlut.edu.cn (Q. Liu), msobaidat@gmail.com (M.S. Obaidat), wgwdut@dlut.edu.cn (G. Wu), gztan@dlut.edu.cn (G. Tan).

https://doi.org/10.1016/j.jss.2017.11.020
0164-1212/

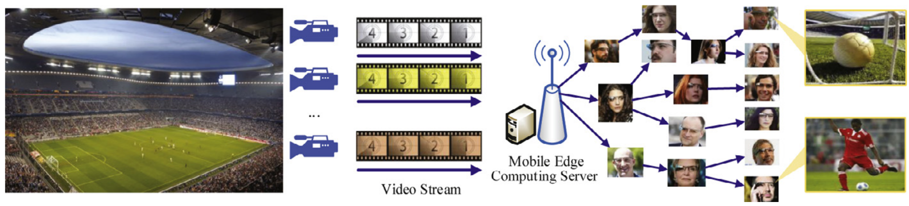

Fig. 1. Tactile Internet application: free viewpoint video.

to edge devices, and thus the system can not only enjoy the benefits of low latency, but can also avoid the problem of network congestion caused by the data transmission. After the rendering, a broadcast tree is usually used to broadcast the encoded video to smart devices like smart glasses carried along by the stadium visitors, since the broadcast tree has several unique properties like high transmission efficiency, high loss recovery efficiency and loss recovery efficiency (Li et al., 2013). At last, the smart device decodes the video of interest and presents them to each visitor. In order to ensure the quality of the user experience, the latency between the naturally visible surroundings by a visitor and the free viewpoint video being displayed on the smart device should satisfy certain criteria. Generally, the latency should not exceed 1ms to avoid cyber sickness by generating a fully synchronized experience (Fettweis, 2014). Therefore, a real-time broadcast tree should be maintained from the MEC server to all end users to meet the latency requirements. In addition, network resources in wireless environment, including device computational power, network bandwidth and device energy, are often severely limited (Lin et al., 2017a). Consequently, an efficient low-cost delay-constraint broadcast tree construction (Lin et al. 2017b, c) is mandatory to make use of the free viewpoint video in practice, where the cost can be defined based on the Signal-to-Noise Ratio (SNR), error rate and energy consumption. This paper focuses on the minimization of the cost on a broadcast tree with delay constraint (i.e., the rooted delay-constrained minimum spanning tree (RDCMST)) to improve the communication resource utilization, such that the broadcast content can be delivered to all destination nodes with minimal communication overhead under the constraints of end-to-end delay. As Theorem 1 given in Section 3, the problem of the RDCMST construction is $\mathcal{NP}$-hard.

There is a rich literature on RDCMST construction (e.g., Gouveia et al., 2008; Salama et al., 1996; Ruthmair and Raidl, 2009; 2010; Xiong et al., 2013); however, most existing solutions have at least one of the following three key limitations. First, they cannot be applied to large-scale RDCMST problem due to the high time complexity. Second, the existing techniques cannot effectively solve the RDCMST problem across all delay bounds. This is undesirable because various delay constraints may be required in the broadcast of Tactile Internet. For example, in the tactile-visual control application, latency of up to 10 ms is acceptable for the seamless video experience, while 1 ms latency is required to move a 3D object with a joy stick (Fettweis, 2012). Third, the existing solutions do not offer sufficient space for the subsequent improvement: since they construct the feasible solution by the sequential addition of edges, which may cause some cumulative errors due to the constraints on end-to-end delay and tree structure. This will affect the quality of solutions even if some heuristic approaches are used to optimize the feasible solution by escaping from local optima with diversification. In order to solve these problems, we have developed a RDCMST construction framework via dynamic algorithm which has the ability to maintain a single-source shortest path tree for the online edge deletions. The network of Tactile Internet is modeled as a connected weighted and undirected graph. Based on some properties of RDCMST, preprocessing techniques are used to discard infeasible and suboptimal edges first, and thus the processing complexity of the algorithm can be reduced. Then edge deletion test is performed with a dynamic graph algorithm according to the order of the edge score, which can minimize the total costs while ensuring the delay-constraint and the tree structure. We have conducted simulations to assess the effectiveness of the proposed framework.

In general, the main contributions of this work are summarized as follows:

- A dynamic algorithm-based RDCMST formation framework is proposed. In contrast to existing solutions, our approach constructs RDCMST via edge elimination, which can reduce cumulative errors and is more suitable for the subsequent improvement;
- The edge score taking account of the adjacency edge cost is introduced under our construction framework to assess how promising an edge that should be handled first;
- A single-source shortest path tree (SSSPT) maintenance algorithm is given to ensure delay-constraint and tree structure in the construction process.

Experimental results show that our proposed method can greatly improve the quality of solutions compared with the existing approaches.

The remainder of the paper is structured as follows. In Section 2, we discuss the related work. In Section 3, we present the related variables used in the broadcast tree construction framework based on dynamic algorithm and the RDCMST problem formulation. The detailed description of RDCMST construction framework based on dynamic algorithm is given in Section 4. In Section 5, we present the experimental results, and conclude in Section 6. Finally, some future works are outlined in Section 7.

2. Related work

With the growing interest in the data transmission for real-time applications in Tactile Internet, several techniques in real-time scenario have inspired some efforts to research the efficient delay-sensitive data transmission infrastructure construction. Many cost-efficient delay-constrained minimum Steiner tree (DCMST) heuristics have been proposed that can be used to construct delay-constrained broadcast trees for Tactile Internet (Leggieri et al., 2014; Oliveira and Pardalos, 2014; Shi et al., 2013; Aijaz, 2016). However, because the DCMST problem is $\mathcal{NP}$-complete even after the delay constraint is removed (Kompella et al., 1992), most of these methods may be too complex to be used for the delay-constrained broadcast tree construction. The RDCMST problem can be reduced from the DCMST problem by making all nodes in the network as destination nodes, which is less complex, but it is still $\mathcal{NP}$-hard. For RDCMST problem, Gouveia et al. presented three theoretically equivalent modeling approaches, and examined some exact approaches to the problem (Gouveia et al., 2008). However, their methods can only solve small-scale graphs for the complete instances. For the large-scale RDCMST problem, Salama et al. presented a solution based on Prim's algorithm, which obtains a feasible spanning tree first, and then improves the solution through