An Energy Efficient Multicast Algorithm for Temporal Networks

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Abstract. Investigating the energy efficient multicast problem in space-ground integrated network (SGIN) is of vital importance for saving satellites transmission resources. However, the time-varying feature of network topology and resources poses great challenges to energy efficient multicast in SGIN. In this paper, we propose an approximation algorithm based on the modified time-expanded graph to minimize energy consumption while completing multicast transmission. At first, the SGIN is depicted by traditional time-expanded graph to capture the correlations between time-varying network resources. Then, to characterize the energy efficient multicast problem for temporal networks, we extend such graph to the Time Expanded Graph for Multicast (TEGM) by adding auxiliary aggregated destination vertices and aggregating edges. Finally, according to TEGM, an approximation algorithm for energy efficient multicast problem is proposed on the basis of the approach presented by Watel to solve the corresponding Directed Steiner Tree problem (DST). Besides, simulation results are conducted to illustrate the superiority of proposed algorithm over that based on dynamic trees.

Keywords: Energy efficient multicast · Space-ground integrated network · Temporal network

1 Introduction

Recently, multicast has gained more and more attentions in wireless communications due to its natural advantage in reducing the spectrum demand and energy consumption [2]. Multicast can be widely used for various applications, e.g., video conference, corporate communication, distance learning and software distribution [5]. In particular, multicast is also with broad application prospects in SGIN. For example, a remote sensing satellite could multicast the observation data to multiple terrestrial sites to save resources of satellite networks. SGIN is a typical temporal network, characterized by long delays, predictable/periodical topology, intermittent connectivity and link disruptions [1]. The time-varying

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feature of SGIN poses a great challenge to enable energy efficient multicast. Therefore, it is prerequisite to construct a precise graph model to characterize the energy efficient multicast problem in SGIN, with the time-varying feature involved. Then, based on such graph model, a Minimum Energy Multicast Tree (MEMT) is constructed to minimize energy consumption.

There have been some works on energy efficient multicast problem in wireless networks and multicast in delay-and disruption-tolerant network (DTN) in the literature. For static wireless networks, the authors in [4] defined the energy efficient multicast problem for the first time. Besides, they proposed a greedy-based heuristic algorithm to generate a multicast tree with the minimum number of transmissions. For DTN, the authors in [7] regarded DTN as a series of snapshots and developed the Dynamic Tree-Based Routing (DTBR) algorithm. Through constructing associated multicast tree in each snapshot, smaller delays and better message delivery ratios can be acquired. Although such approach takes into account the time-varying feature, it ignores the correlations between time-varying resources, which would cause the unavailability of some network resources.

In this paper, we propose an energy efficient multicast approach for temporal networks (e.g., SGIN) to minimize energy consumption. First, in order to characterize the correlations between time-varying network resources, we leverage the traditional time-expanded graph (TEG) [3] to model the temporal network. Then, through adding some corresponding aggregated destination vertices and aggregating edges on the legacy TEG, the Time Expanded Graph for Multicast (TEGM) is proposed to characterize the Energy Efficient Multicast problem (EEM) for temporal networks. Next, on the basis of the TEMG, we present an approximation algorithm based on the approach to solve the corresponding DST to minimize energy consumption. Finally, an instance without loss of generality is given to illustrate that our proposed algorithm can further reduce energy consumption when completing the multicast transmission.

2 System Model

Due to satellites definite orbital movement, the topology of SGIN is time-varying and predictable. The planning horizon $[0, T)$ can be divided into m time intervals. Assume that the topology remains fixed during each interval τ_i, but changes immediately between intervals. As shown in Fig. 1, we use a series of snapshots to describe the system as:

- *Source vertex sv*, representing the remote sensing satellite, which can transmit observation data.
- *Destination vertices* $DV = \{dv_1, dv_2, ...dv_n...\}$, representing multiple terrestrial sites, which receive observation data.
- *Optional vertices* $OV = \{ov_1, ov_2, ...ov_n...\}$, representing other satellites in the network, which can be selected to relay observation data when generating multicast routes.

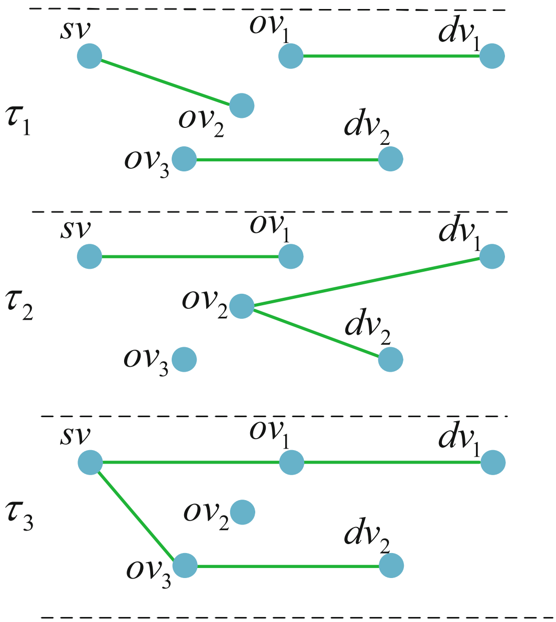

Fig. 1. System described by snapshot with 3 time intervals.

Besides, the edges between different vertices in each time interval indicate that they can transmit data to each other.

In Fig. 1, *sv* starts a multicast session at $t = 0$, and needs to send the observation data to all vertices in emphDV by multicast. We do not consider multipath transmission and assume that a vertex would consume a certain amount of energy whenever it forwards data. Therefore, to enable the minimum-energy multicast, it is of vital importance to select relay nodes and then build the multicast tree with the minimum number of transmissions.

3 Problem Formulation

3.1 Time Expanded Graph for Multicast

In this subsection, we develop the traditional TEG to the TEGM so as to utilize the correlation between time-varying resources and solve the multiple duplicates of the same destination node in the graph. TEGM is shown in Fig. 2, denoted by $G(V,E,W)$ as:

– V is the set of vertices, the components ($V_{sv} = \{sv^i\}$, $V_{dv} = \{dv_n^i\}$ and $V_{ov} = \{ov_n^i\}$) of which correspond to the duplicates of the sv, DV and OV in each time interval. We add *aggregated destination vertices* $ADV = \{adv_1, adv_2, ..., adv_n, ...\}$ to abstract and aggregate the duplicates of each

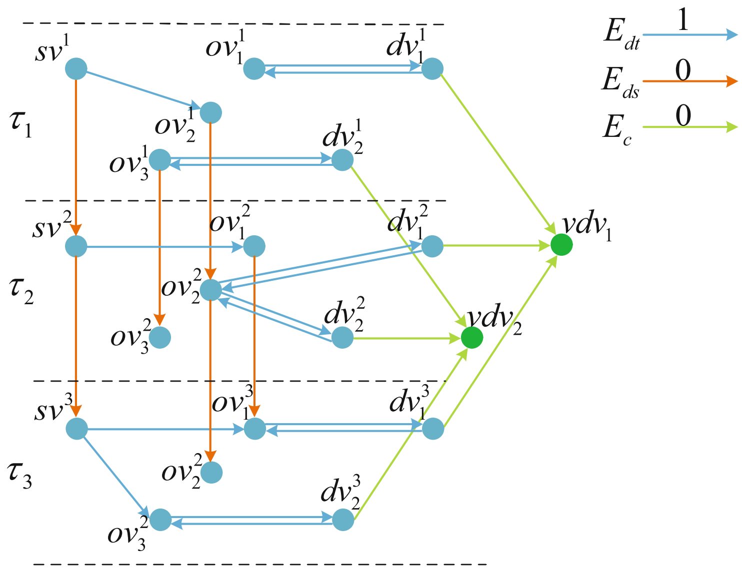

Fig. 2. TEGM.

destination node. The reason is that multiple duplicates of the same destination node in the traditional TEG, would make it difficult to ensure that each destination node only receives multicast data once. Therefore, $V = V_{sv} \cup V_{dv} \cup V_{ov} \cup ADV$.

- E, a set of directed edges, consists of *data transmission edges*, *data storage edges* and *aggregating edges*. The *data transmission edges* $E_{dt} = \{(v_k^i, v_n^i)|v_k^i \in V_{sv} \cup V_{ov}, v_n^i \in V_{dv} \cup V_{ov}\}$ exist between different vertices in the same time interval, indicating that these vertices can transmit data to each other. The *data storage edges* lie between two duplicates of the same vertices at adjacent intervals, which can be denoted as $E_{ds} = \{(v_n^i, v_n^{i+1})|v_n^i, v_n^{i+1} \in V_{sv} \cup V_{ov}\}$. Considering that the remaining storage resources of satellites are limited, the *data storage edges* between duplicates of some vertices at adjacent intervals are not available. The *data storage edges* could characterize the ability of vertices to cache data, which is quite important for correlating network resources in adjacent time intervals. Specially, we add *aggregating edges* $E_a = \{(dv_n^i, vdn_n)|dv_n^i \in V_{dv}\}$ to associate the duplicates of destination vertices in each time interval with their corresponding virtual destination vertices.
- M, a set of metrics, indicate different types of edges in E. The corresponding metric M_{dt} for *data transmission edges* is set to 1, indicating that a vertex has to transmit once when sending data to its neighbors. For *data storage edges*, the element in can be written as M_{ds}. Since caching data does not consume the transmission energy of vertices, M_{ds} is equal to 0. In addition, since the *aggregating edges* are virtual links, their corresponding metric M_a is also set to 0.

3.2 An Approximation Algorithm for Energy Efficient Multicast Problem

In this subsection, with the proposed TEGM, the definition of EEM is presented. In addition, inspired by the approach of solving Directed Steiner Tree problem [6], we propose an approximation algorithm for generating a feasible Minimum Energy Multicast Tree (MEMT) to minimize the energy consumption.

Energy Efficient Multicast Problem in Temporal Networks: Given a TEGM, generate a directed tree $G(V,E,W)$ with the minimum number of transmissions, which is rooted at $sv^1 \in V_{sv} \subseteq V$ and spans all vertices within $VDV \subseteq V$.

Directed Steiner Tree Problem over TEGM: Given a TEGM, denoted as $G(V,E,W)$, we aim to find a minimum *cost* directed tree rooted at $sv^1 \in V_{sv} \subseteq V$ spanning all elements in $VDV \subseteq V$, with *cost* as the sum of weights on all edges.

Assume $T(V^*, E^*, W)$ is an approximate MEMT for corresponding EEM. Note that, not all vertices in V^* have to transmit data. Since some vertices in the original TEGM have no associated *data storage edges*, it can be considered that the number of transmissions is equivalent to that of *data transmission edges* in T. Nevertheless, the number of *data transmission edges* equals the sum of weights on all edges in E^*, i.e. *cost*. Therefore, through solving the corresponding DST over TEGM, we can find a feasible MEMT.

Algorithm 1. An approximation algorithm for EEM.

1: **Input:** A given TEGM $G(V,E,W)$.
2: **Output:** A feasible MEMT T.
3: **Construct** the complete digraph $G'(V', E', W')$ from G such that $V' = sv^1 \cup VDV$, and each element in E corresponds to a directed shortest path in G'. Besides, W' represents the distance of directed shortest path between any two vertices in V', or is set to 0 if such path is not available.
4: **Construct** the minimal directed spanning tree T' rooted at of sv^1 of G'. (Whenever there are several minimal directed spanning trees, pick an arbitrary one.)
5: **Develop** the directed subgraph $G_s{}'$of G' by replacing each edge in T' to its corresponding directed shortest path in G'. (When there are several directed subgraphs, select the one with the minimal sum of edge weights.)
6: **Find** the minimal directed spanning tree T rooted at sv^1 from $G_s{}'$ (When there are several minimal directed spanning trees, pick an arbitrary one.), which is an approximate Minimum Energy Multicast Tree.

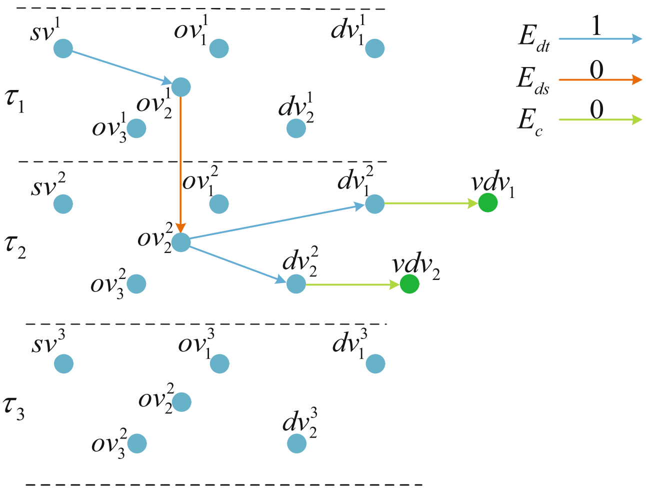

Fig. 3. MEMT for the SGIN.

4 Simulation

In this section, on the basis of the SGIN in Fig. 1, we separately apply the proposed approximation algorithm and DTBR algorithm to solve EEM. Through comparing the number of transmissions (i.e., energy consumption) and that of time intervals (i.e., delay) required to enable energy efficient multicast, the superiority of our algorithm can be verified.

The MEMT constructed by our algorithm in shown in Fig. 3. To accomplish the multicast transmission with the minimum energy consumption, data needs to be transmitted from sv to ov_2 during τ_1. ov_2 would cache the data until τ_2, and then distributes it to dv_1 and dv_2 in a single transmission.

A series of dynamic trees generated by the DTBR algorithm are shown in Fig. 4. Note that, the only available dynamic tree lies in the third snapchat. Therefore, within τ_3, data would be transmitted from sv to ov_1 and ov_3, and be relayed to dv_1 and dv_2 respectively.

Figure 5 shows the number of transmissions and time intervals required to complete multicast transmission. It is obvious that our algorithm can acquire less energy consumption and smaller delays than the DTBR algorithm.

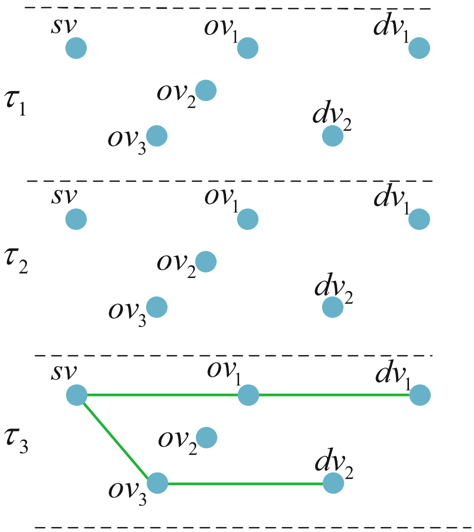

Fig. 4. Dynamic trees constructed by DTBR algorithm.

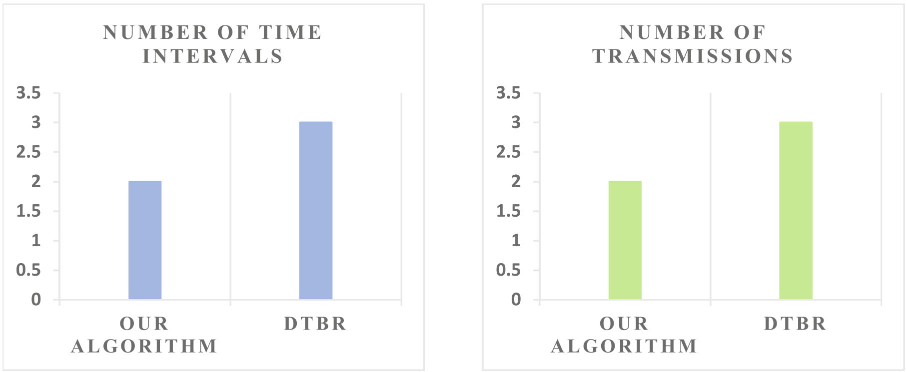

Fig. 5. Number of transmissions and time intervals.

5 Conclusion

In this paper, we propose an approximation algorithm for the energy efficient multicast problem in temporal networks based on the modified TEG to minimize the energy consumption. Specially, the modified TEG is constructed by adding some corresponding *aggregated destination vertices* and *aggregating edges* in the traditional TEG. Simulation results illustrate that our proposed algorithm can achieve less energy consumption and smaller delays compared to the DTBR.

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